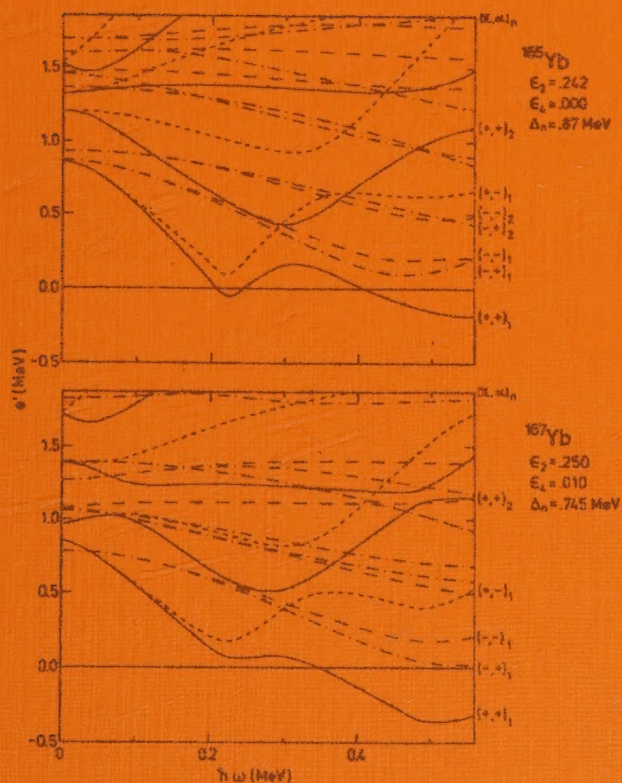




A STUDY OF HIGH-SPIN STATES IN RARE-EARTH NUCLEI

Nirabendu Roy



LUND 1981

COSMIC AND SUBATOMIC PHYSICS REPORT
LUIP 8108
CODEN: LUNFD6/(NFFK-8108)1-28(1981)
ISSN 0348-8329

A STUDY OF HIGH-SPIN STATES IN
RARE-EARTH NUCLEI

NIRABENDU ROY

Akademisk avhandling som för avläggande av filosofie
doktorsexamen vid matematisk-naturvetenskapliga fakul-
teten vid universitetet i Lund kommer att offentligt
försvaras å Fysiska Institutinens föreläsningssal B
fredagen den 4 december 1981 kl. ~~10.15.~~

14.00



Organization LUND UNIVERSITY Department of Physics, Sölvegatan 14, S-223 62 Lund, Sweden		Document name DOCTORAL DISSERTATION	
		Date of issue 1981-12-04	
		CODEN: LUNFD6/(NFFK-8108) 1-28 (1981)	
Author(s) NIRABENDU ROY		Sponsoring organization	
Title and subtitle A Study of High-Spin States in Rare-Earth Nuclei			
Abstract High-spin states in rare-earth nuclei ^{149}Gd, ^{165}Yb, ^{166}Yb and ^{167}Yb have been investigated by means of techniques of in-beam γ-ray spectroscopy. Most of the levels in ^{149}Gd can be understood qualitatively in terms of configurations involving 3 valence neutrons in $f_{7/2}$, $g_{9/2}$ and $i_{13/2}$ orbitals just above the $N=82$ gap and the octupole state of the ^{146}Gd core. The 44 ± 11 W.U. $E3$ strength of a $27/2^+$ isomer at 3.4 MeV is in accordance with the systematics. Moderate agreement between calculated and experimental energies of the $f_{7/2}^3$ multiplet suggests long range contributions at $N=85$. Particle-rotor model is found to provide a good description of the decay branchings from, and the energies along the g.s.b. and S-band in ^{166}Yb. Comparison of multiple-quasineutron Routhians, constructed from one-quasineutron Routhians in $^{165,167}\text{Yb}$, with the experimental ones in $^{165-167}\text{Yb}$ suggest for ^{166}Yb, a 300 keV attractive residual interaction between two quasineutrons, independent of $\hbar\omega$ or configuration. Signature-splitting and crossing frequencies in the $i_{13/2}$ band are not reproduced in CSM calculations. Signature dependence of matrix elements for $I \rightarrow I-1$ $M1/E2$ transitions in $i_{13/2}$ band is borne out by the experimental data on $^{165,167}\text{Yb}$. Reproduction in CSM, of a systematic odd-even effect found in the lowest-frequency band crossing in $N=90-102$ nuclei, requires values of Δ_n, lower for odd-N nuclei than for even-N nuclei. Comparison of Δ_n values obtained in this way with the odd-even mass differences suggest possibilities of obtaining quantitative information on the neutron pairing-correlation parameter from these values of Δ_n used in CSM.			
Key words shell model, Cranked shell model, interaction, isomer, quasineutron, alignment, Routhian, particle-rotar model, crossing frequency, band crossing, signature			
Classification system and/or index terms (if any)			
Supplementary bibliographical information			Language English
ISSN and key title ISSN 0348-8329			ISBN
Recipient's notes		Number of pages 28	Price
		Security classification	

Distribution by (name and address)

Department of Physics, University of Lund, Sölvegatan 14, S-223 62 Lund, Sweden
 I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature Nirabendu Roy

Date 81-11-03



Digitized by the Internet Archive
in 2026

https://archive.org/details/IA41553424_0004

1. General Outline

With the advent of heavy-ion accelerators and with the development of improved experimental techniques, it has become possible to pursue the study of nuclei into the regime of high angular momenta, a regime where the internal stresses associated with the centrifugal and Coriolis forces modify the nuclear structure in a major way. One of the major problems concerns the study of the yrast region (states, each characterized as being the lowest excited state for a given angular momentum, are termed yrast states). In the angular momentum vs energy plane, the yrast line forms the boundary between the physically possible states and the impossible states. The nucleus is cold in the yrast region, in that almost all the excitation energy is tied up in generating angular momentum. The study of nuclei in the yrast region may yield quantitative information regarding modifications of nuclear structure under rapid rotation.

Onset of fission limits the amount of angular momentum that a compound nucleus formed in a heavy-ion fusion reaction can accommodate. Figure 1, based on rotating liquid drop model calculations due to Cohen, Plasil and Swiatecki (ref. 1), depicts the limiting angular momentum as a function of the mass number for the β -stable species of nuclei. Along the curve labelled $B_f=8$, the fission barrier equals 8 MeV, and for compound nuclei lying below that curve, neutron emission dominates over fission.

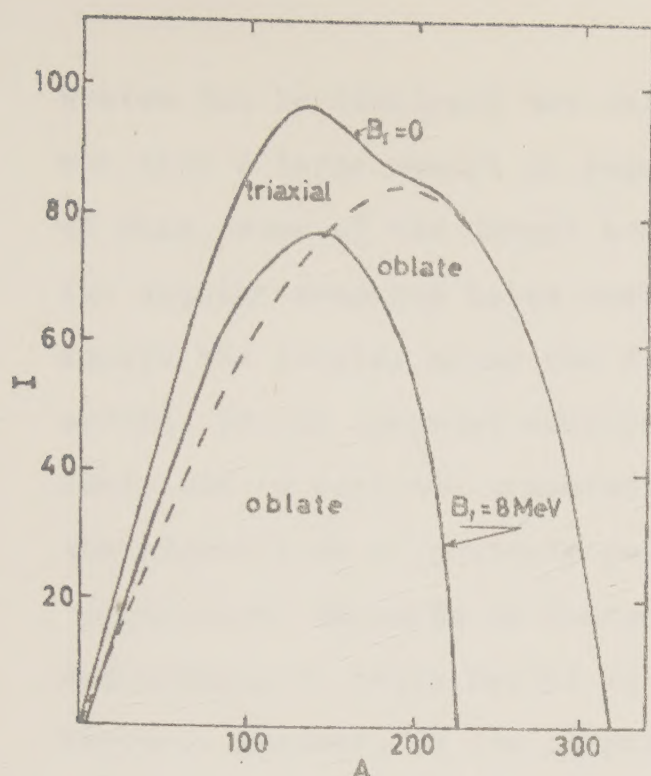


Fig. 1. The limiting angular momentum that can be accommodated by a β -stable nucleus is shown as a function of the mass number. The figure is taken from ref. 1.

The average amount of angular momentum brought into the compound nucleus by a heavy ion depends upon the beam energy and the target-projectile combination used. In a typical case, for example the $^{154}\text{Sm} + ^{16}\text{O} \rightarrow ^{170}\text{Yb}^*$ reaction at an energy of 80 MeV (used in the present work), the R.M.S. value of the angular momentum of the compound nuclei, as calculated with the fusion-evaporation code ALICE (ref. 2), is about $25\hbar$. The same compound system can be reached in the $^{130}\text{Te} + ^{40}\text{Ar}$ reaction at about 160 MeV, resulting in an almost two-fold increase in the input angular momentum.

The excitation energy of the compound nuclei formed in heavy-ion fusion reactions lies far above the threshold for particle emission. Many overlapping states are excited simultaneously and statistical concepts can be applied to the decay of the compound system. In its decay, the compound

system has to dissipate not only a large amount of energy but also a large amount of angular momentum. As a consequence of this, most of the decays are of the stretched type, i.e., the angular momentum taken away by a particle or a photon equals the initial minus the final spin values of the compound system. If the compound nucleus does not undergo fission, it cools off by particle evaporation, usually neutrons, until the probability of particle-emission falls below that of γ -emission. Emission of charged particles (p, α) from medium-mass or heavy nuclei is hindered by the Coulomb barrier. However, if the compound nucleus is a very neutron-deficient one or a light one, the emission of charged-particles may compete favourably with neutron emission and may even override it.

Neutron evaporation continues until the excitation energy comes down to about one neutron separation energy from the yrast line. Figure 2, based on the statistical decay code GROG12, shows the decay of the compound nucleus ^{164}Er populated in the $^{124}\text{Sn} + ^{40}\text{Ar}$ reaction at 147 MeV. The shaded regions show the regions reached after the evaporation of 3-5 neutrons where γ -emission competes with neutron emission. When γ -emission has become the main decay mode, the nucleus cools down to a region a few MeV above the yrast line by means of a number of statistical electric dipole transitions. This region is characterized by a number of collective bands roughly parallel to the yrast line and their crossings. The deexcitation then proceeds mainly along

STATISTICAL MODEL CALCULATIONS

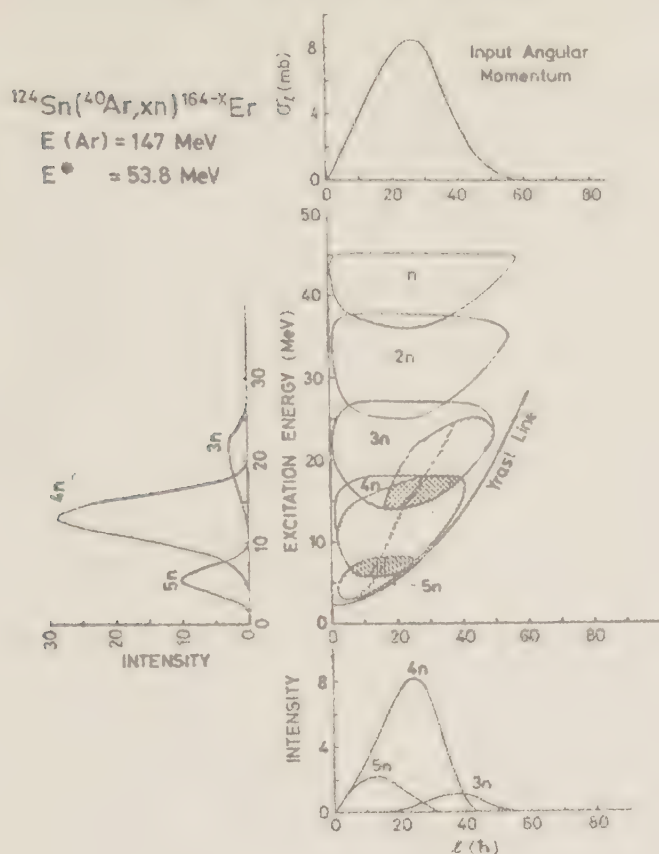


Fig. 2. Statistical-code predictions for the decay of ^{164}Er formed in $^{124}\text{Sn} + ^{40}\text{Ar}$ reaction at 147 MeV. γ -ray emission competes with neutron evaporation in the shaded regions, reached after the evaporation of 3-5 neutrons. Entry populations for the 3n-5n evaporation residues are also shown as a function of angular momentum and excitation energy. The figure is taken from ref. 3.

these bands by means of enhanced and stretched E2 transitions. Interband E2 transitions, particularly from higher lying bands to lower lying bands, are strong at the band crossings. The yrast and the near-yrast transitions thus gain in intensity down along a cascade. Individual transitions at this stage are, however, too feeble to be resolved as discrete lines in the spectrum. These γ -rays form a continuum spectrum extending to about 1.6 MeV and are called the continuum γ -rays. Level scheme studies by means of spectroscopy of discrete lines cannot be pursued into this region. Experimental techniques, involving correlation of the γ -energies (see ref. 4 and the references therein), have been developed to explore the gross behaviour of the

collective bands and their crossings in this region.

Subsequent cooling brings the nucleus to a region where the yrast and the near-yrast transitions have gained sufficient intensity to make their appearance as discrete lines. These transitions can be studied individually so as to deduce level schemes. At present, $38\hbar$ seems to be the limiting value of spin up to which detailed spectroscopic information can be obtained in some cases.

If the nucleus is prolate in the ground state, then the experimental level scheme consists mainly of a number of collective bands of rotational or vibrational origin. The basic characteristics of a collective band are the regular sequence of transition energies and the enhanced E2 transitions among members of the band. A consequence of the Coriolis and centrifugal forces in rotating nuclei is the tendency of the valence nucleons to align their spins with the collective angular momentum. This results in many rotational nuclei structural changes along the yrast line due to rotational alignment of high-j nucleons. In other words, for certain values of the angular momentum along the yrast line (usually around $14\hbar$ in even-even rare-earth nuclei), it becomes energetically more favourable for the nucleus to form a yrast state by breaking a pair of high-j nucleons and aligning their angular momenta with that of the collective motion than by generating angular momentum by collective motion alone. This is the Rotational Alignment picture originally suggested by

Stephens and Simon (ref. 5) as an explanation of the backbending effect (ref. 6). However, bandcrossings and backbending should not be a feature pertinent to the yrast band alone. Near the yrast line, there should exist many 2 q.p. or 1 q.p. (in odd nuclei) bands, which would also experience backbending or upbending due to the rotational alignment of a pair of high-j quasiparticles near the Fermi surface ($i_{13/2}$ neutrons or $h_{11/2}$ protons in the case of rare-earth nuclei). A study of not only the yrast band but also of other bands is thus imperative for a proper understanding of the influence of rotation on quasiparticles near the Fermi surface.

The cranked shell model and the particle-rotor model have been the theoretical approaches used in the present studies to understand the band structure. Both these models invoke the idea of a statically deformed field that rotates with respect to the laboratory frame of reference. The main idea of the particle-rotor model is to represent the majority of the nucleons by a rotor having rotational degrees of freedom only, and to treat the degrees of freedom of one or a few remaining nucleons explicitly. The particle-rotor Hamiltonian refers to the laboratory system and properties of various states are calculated as functions of angular momentum. On the other hand, the cranking model, due to Inglis, deals with the motion of the nucleons in a rotating frame of reference. All nuclear properties are expressed explicitly as functions of the rotational

frequency and, in order to compare these results with the experimental values, these results may be converted into functions of angular momentum. However, it is easier to go the other way round, i.e., to convert the experimental information contained in the decay scheme to quantities in the intrinsic rotating frame. The interpretation of the band structure and band crossings along the lines of Bohr and Mottelson (ref. 7) provides us with a means to compare the experimental results with a microscopic theory and to extract quantities like the crossing frequency and the aligned angular momentum from the experimental data. These methods have been further elaborated by Bengtsson and Frauendorf (ref. 8).

Collective motion, i.e., coherent superposition of small changes in the motion of a large number of nucleons, is not the only way to generate high-spin states. High-spin

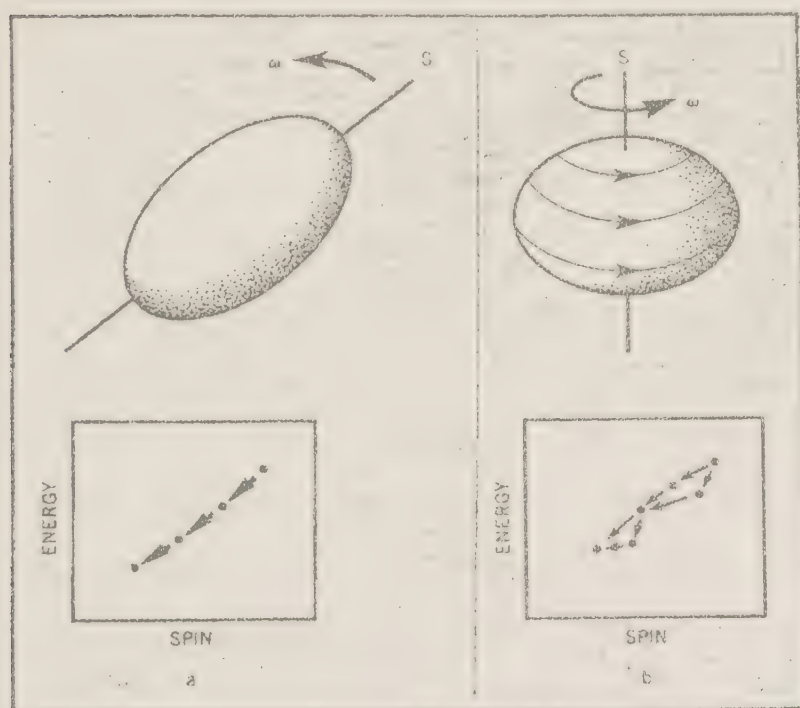


Fig. 3. Two different ways of generating high angular momentum and the corresponding structure along the yrast line, a) collective rotation and b) alignment of angular momenta of individual nucleons. The figure is taken from ref. 9.

states may also be generated by large changes in the orbits of a few nucleons. High-spin states may thus be generated by a few high- j nucleons rotating around the symmetry axis. This coupling scheme is often referred to as the rotation about the symmetry axis and is appropriate for the generation of the yrast states in the regions of the periodic table where there is a concentration of high- j orbitals low in energy. Contrary to the well-developed band structure associated with collective motion, the spacings of the yrast levels in such a coupling scheme are highly irregular. The yrast cascade forms an interwoven sequence of dipole, quadrupole and occasionally of higher multipole transitions. The electromagnetic transitions usually involve changes in the orbits of a single or a few nucleons and are essentially of single-particle strength. Figure 3 depicts schematically the formation of the yrast states and the structure along the yrast line in these two different coupling schemes.

The occurrence of very high-spin isomers formed by the alignment of the angular momenta of individual nucleons was predicted by Bohr and Mottelson (ref. 10). In a subsequent survey work, an island of high-spin isomers was discovered at proton and neutron numbers slightly above 64 and 82 respectively (ref. 11). Since then, detailed spectroscopic studies have been made on a number of nuclei in this region with $Z \approx 64$ and $N \approx 82$. From the study of ^{146}Gd and its neighbouring

nuclei, the proton shell closure at $Z=64$ and its implications for the yrast isomers in the $A \approx 150$ region was pointed out (ref. 12). Calculations (ref. 13), dealing specifically with nuclear shapes and isomerism in nuclei around ^{146}Gd , suggest spherical or slightly oblate shapes for the ground states and even for very high-spin states in these nuclei. High- j orbitals like $h_{9/2}$, $f_{7/2}$ and $i_{13/2}$ for neutrons and $h_{11/2}$ for protons appear just above the shell-gap at $Z=64$ and $N=82$ and are of crucial importance for the formation of high-spin states in this region. Furthermore, it was shown (ref. 12) that the shell-model approach in the ^{208}Pb region (ref. 14,15), where the empirical single-particle (hole) energies and their mutual interactions are employed in the calculations of the level energies, can also be applied in the ^{146}Gd region. Particular importance should be attached to the occurrence of the 1.58 MeV $I=3^-$ level as the first excited state in ^{146}Gd , a property which it shares only with ^{208}Pb . The low energy of the 3^- octupole state gives rise to a number of yrast states by the coupling of this 3^- state to particle-hole excitations, rather than by particle-hole excitations alone.

This dissertation is based on the following publications dealing with the study of high-spin states in rare-earth nuclei :-

- 1) High-spin shell model excitations in ^{149}Gd
Zeitschrift Für Physik A300 (1981) 133
- 2) High-spin band structure in ^{166}Yb
Proceedings of the Nobel Symposium on "Nuclei at Very High Spin, Sven Gösta Nilsson in Memoriam"
Physica Scripta 24 (1981) 324
- 3) Near-yrast spectroscopy of $^{165-167}\text{Yb}$
Cosmic and Subatomic Physics Report, Lund
LUIP 8107 LUNFD6/(NFFK-7008) 1-43(1981) ISSN-0348-9329
Submitted for publication in Nuclear Physics A
- 4) Evidence for Decreased Pairing Energies in odd-N Nuclei from Band-Crossing Frequencies
Physical Review Letters 47 (1981) 75

2. Experimental Techniques

The experimental techniques utilised in the experiments were the methods of in-beam γ -ray spectroscopy, based on the studies of excitation functions, angular distributions, γ - γ coincidences, conversion electron coefficients, linear polarisation and life-times.

In the excitation function measurements, γ -ray singles spectra are obtained for a number of bombarding energies. The beam energies are chosen so as to span a range which includes the expected optimum for the production of the particular nucleus. The intensities of the γ -rays are normalised to some low-lying transition in the pertinent nucleus. As a function of the beam energy, these normalised intensities show different behaviour according to the nuclei of origin. In general, γ -rays emanating from nuclei with one neutron more or less than the pertinent nucleus can be easily discriminated. Moreover, information about the optimum beam energy and intuitive guidance into the ordering of the transitions are obtained.

Most important data for the assignment and ordering of the transitions comes from the coincidence studies. In a typical coincidence experiment, two Ge(Li) detectors are used. γ -rays triggering the detectors within a certain time interval are digitalised and recorded on magnetic tapes for off-line analysis. The low coincidence count rate attainable with such a two-detector system

is not suited for the study of weakly populated bands, for which high statistics is of prime importance. The use of many detectors can solve this problem. For example, the use of four detectors would increase the coincidence count rate by a factor of about 6 when compared to a 2-detector system. In the coincidence experiment on ^{166}Yb , 4 Ge(Li) detectors were used. The gains of the detectors were matched to be equal so that the resultant spectra could be added. Furthermore, 4 NaI(Tl) detectors were incorporated, serving as multiplicity filters. Only those events were recorded in which at least three detectors, of which at least two were Ge(Li) detectors were triggered. The coincidence count rate was approximately 1000 counts/sec, using a 1 particle nA beam of 80 MeV ^{16}O on a 1.5 mg/cm^2 ^{154}Sm target. A similar set-up, in which one of the Ge(Li) detectors was replaced by a planar Ge(Li) detector, was used for the coincidence experiment on ^{167}Yb . These set-ups favour high-multiplicity events and virtually eliminate all events due to radioactivity. This is important when studying weak transitions as the product nuclei are usually highly radioactive.

The coincidence experiment on ^{165}Yb was performed with a set-up consisting of 5 Ge(Li) detectors in Compton-suppression shields. This set-up reduced the background drastically, permitted easy and positive identification of weak transitions in the gated spectra

and made it possible to gate on weak transitions. The suppression of the Compton events resulted in an almost 5-fold reduction in the amount of the data to be handled. Furthermore, the use of 5 detectors rendered it feasible to run the coincidence experiment with a reasonable counting rate. A 3 particle nA beam of 80 MeV ^{17}O on a 2.5 mg/cm^2 target of ^{152}Sm resulted in about 400 Compton-suppressed coincidences/sec.

The idea of elucidating the multipole nature of the transitions by measuring the angular distribution of the γ -rays stems from the fact that the compound nuclei formed in a heavy-ion fusion reaction are highly aligned with respect to the beam direction. The orbital angular momentum of the projectile, the main contributor to the high angular momentum of the compound nuclei, lies in a plane perpendicular to the beam direction for geometrical reasons. Due to the predominantly stretched character of the transitions, the compound nuclei remain aligned in a plane normal to the beam axis during the deexcitation process (The presence of isomeric states with life-times tens of nanoseconds or more will attenuate and eventually destroy the alignment). The γ -rays thus evince directional anisotropy down to the lowest members of a cascade. In practice, singles γ -ray spectra are acquired at several angles with a moveable detector, the beam being monitored by a stationary detector. The intensities of the γ -rays

at different angles are normalised to the monitor yields, corrected for the dead times and fitted to an expression

$$\begin{aligned} W(\theta) &= A_0 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta) \\ &= A_0 (1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)) \end{aligned}$$

The coefficients a_2 and a_4 , after correction due to finite solid angles of the detectors used, are usually sufficient to determine the multipole nature ($L=1,2,3$) of the γ -rays and thence the spins of the levels.

The combination of the angular distribution data with the data from the electron conversion measurements or the data from linear polarisation measurements suffices for an unambiguous assignment of the electric or the magnetic nature of the transitions and hence the spins and parities of the levels. In the electron conversion process, direct one-step transfer of excitation energy from the nucleus to one of its orbital electrons causes the electron to be ejected with an energy equal to the energy of the relevant gamma minus the electron binding energy. The electrons are focussed on to some detector (usually Si(Li) detectors) by means of magnetic fields. The conversion electron spectrum is obtained either by recording the spectrum from the detector, or, by varying the magnetic field and using it as a momentum selector or a combination of both. The electron conversion coefficients are evaluated from the experimental electron intensities and a knowledge about the efficiency of the electron spectrometer, the relative intensity of the γ -rays and the multipole nature of a few strong transitions.

The γ -rays emitted from aligned nuclei evince linear polarisation. The differential cross-section for Compton scattering depends on the angle between the polarisation vector and the scattering plane. This fact is utilised in the measurement of the linear polarisation. This is most efficiently measured at $\theta=90^\circ$. The asymmetry in Compton scattering in a plane containing the beam axis and in a plane perpendicular to it can be expressed as a product of two factors ; a factor which varies smoothly with energy and depends upon the target-detector geometry used and a factor which depends on the angular distribution coefficients and the electric or magnetic nature of the transitions. In the experiment on ^{149}Gd , two Ge(Li) detectors were used, one placed 25 cm beneath the target serving as a scatterer and the other face to face with the first one at a distance of 8 cm. The second detector was shielded from the target by 8 cm of lead and served as the absorber. The coincidence events were recorded on magnetic tapes for two positions of the detector system, one with the axis of the system parallel to the beam axis and the other with it perpendicular to the beam direction. The gains of the two detectors were matched. The beam was monitored with a fixed detector. In the off-line analyses, the events on the magnetic tapes from the two detectors were added to obtain the resultant spectra. The measurement of linear polarisation was crucial in deducing the parity of the isomer at 3.4 MeV.

The use of pulsed beams makes it possible to identify and measure the lifetimes of high-spin isomeric states by recording the time distribution of the γ -rays with respect to beam bursts. However, the time distribution method is not well-suited for measuring short half-lives ($<$ time resolution). It can be shown that the centroid of the time distribution of the γ -rays from an isomeric state gets shifted by an amount $1/\lambda$ compared to that for γ -rays without any delayed component. Preliminary experiments on ^{149}Gd clearly indicated the presence of two isomeric states, one with a half-life of about 5 ns and the other one with a much shorter half-life. Subsequent experiments, measuring the time distribution of the γ -rays relative to the cyclotron beam bursts, resulted in the determination of the half-lives of the isomeric states at 3.4 MeV and 0.87 MeV. The time distribution of the delayed components led to the assignment of a half-life of 6 ns to the former one, and the centroid-shift method gave 1.6 ns as the half-life of the latter one.

3. Discussion

3.1. Paper I

Paper I deals with the experimental study of ^{149}Gd with three valence neutrons outside the ^{146}Gd core, in a Lund-Jülich-Stockholm collaboration. The experiments were conducted partly at the cyclotron at AFI, Stockholm and partly at the cyclotron at KFA, Jülich.

High-spin states have been identified up to about 5 MeV. Most of the states can be understood qualitatively in terms of configurations involving 3 valence neutrons in the $f_{7/2}$, $h_{9/2}$ and $i_{13/2}$ orbitals just above the $N=82$ gap and the octupole 3^- state of the ^{146}Gd core.

Many features of the $N=85$ isotones ^{147}Sm , ^{149}Gd , ^{151}Dy and ^{153}Er are found to be remarkably similar. All these nuclei have the $(\nu f_{7/2}^3) 7/2^-$ configuration in the ground state. The $11/2^-$ and $15/2^-$ members of the $\nu f_{7/2}^3$ multiplet occur at similar excitation energies in all these isotones.

The calculation of level energies in ^{149}Gd using the formalism of angular momentum algebra (ref. 16) is beset with difficulties. Empirical knowledge about the single-particle energies near ^{146}Gd and their mutual interactions is rather incomplete. Of the three neutron orbitals, $f_{7/2}$, $h_{9/2}$ and $i_{13/2}$ just above the $N=82$ gap, the $i_{13/2}$ level has not been identified in ^{147}Gd . Only the 8^+ member of the $h_{9/2}f_{7/2}$ neutron multiplet is known in ^{148}Gd . Moreover,

the $Z=64$ gap has been shown to decrease rapidly when neutrons are added to the ^{146}Gd core (ref.17). Nuclei with $N>88$ have been known to be prolate deformed in their ground states. The low energy of the 3^- octupole state complicates the situation further, giving rise to a number of low-lying states by coupling to the particle(hole) states.

The energies of the $\nu f_{7/2}^3$ multiplet are reproduced only moderately, implying the effect of long range contributions already at $N=85$.

Incomplete knowledge of the $\nu h_{9/2} f_{7/2}$ interaction energies hinders a detailed comparison of the calculated and the experimental energies of the $h_{9/2} f_{7/2}^2$ multiplet, of which the $J^\pi = 9/2^-, 13/2^-, 17/2^-$ and $21/2^-$ states have been identified in the present work. Decay branchings suggest the mixed $17/2^-$ level at 2232 keV to have a predominantly $\nu h_{9/2} f_{7/2}^2$ component.

The excitation energies and the energy separations of the $J^\pi = 11/2^+, 13/2^+, 17/2^+$ and $21/2^+$ levels suggest them to have a predominantly $\nu f_{7/2}^3 \times 3^-$ configuration, somewhat mixed with the $\nu i_{13/2} f_{7/2}^2$ configuration. The $25/2^+$ state cannot be formed by coupling the 3^- state to the $f_{7/2}^3$ states. The assignment of $\nu i_{13/2} f_{7/2}^2$ configuration to this state leads to an indirect estimate of the $\nu i_{13/2}$ single-particle energy, about 2 MeV higher than the $\nu f_{7/2}$ energy, and this result agrees with other indirect evidences.

The isomeric state at 3.4 MeV has been found to have an E3 strength of 44 ± 11 W.U. This isomeric state has been assigned a predominantly $(\nu f_{7/2}^2 \times h_{9/2}) 21/2^- \times 3^-$ configuration. The measured E3 transition rate compares favourably with that measured in $^{147,148}\text{Gd}$ and is probably somewhat larger than that in ^{146}Gd . This is to be expected, since the $f_{7/2} \rightleftharpoons i_{13/2}$ transitions of the neutrons in the $f_{7/2}$ orbital would contribute to the 3^- strength in Gd nuclei with $N > 82$.

The measured neutron E2 effective transition charge $(4.0 \pm 0.2)e$, compares favourably with that found in neighbouring nuclei.

Three levels with $J^\pi = 17/2^-$, $19/2^-$ and $23/2^-$ come so low in energy that it is difficult to interpret them as particle(hole) excitations. They have been tentatively suggested as having configurations involving coupling of two 3^- octupole phonons to the members of the $\nu f_{7/2}^3$ multiplet. This interpretation is in accordance with the systematics of the 3^- energy in the ^{146}Gd region.

3.2. Paper II

Papers II and III deal with the experimental study of the nuclei $^{165,166,167}\text{Yb}$ in a collaboration with the Niels Bohr Institute, Copenhagen. The experiments were carried out at the NBI tandem accelerator using 80-84 MeV beams of $^{16,17,18}\text{O}$ on $^{152,154}\text{Sm}$ targets.

The work described in paper II has led to the identification of six collective bands in ^{166}Yb . The ground-state band has been established up to its 18^+ member, and the S-band from its 12^+ state to the 24^+ state. Two negative parity bands have been identified to quite high spins, 22^- and 23^- respectively. These two negative parity bands are probably the two lowest 2 q.p. bands with different signatures, based on neutron levels $[642] 5/2^+$ and $[523] 5/2^-$ at zero frequency. A few members of the γ -band and a band with unassigned spins and parities have furthermore been observed.

The crossing between the ground-state band and the S-band in ^{166}Yb is endowed with a special feature. It is the only known case in the rare-earth nuclei, where all the four interband and intraband transitions at the crossing point have been experimentally identified. The reason is ascribed to be the smallness of the interaction matrix element between the two bands associated with a crossing spin in between even integer values. The observed branching ratios at the crossing point do indeed suggest a small interaction matrix element of the order of 45-50 keV, and a two-band analysis gives $I_c \sim 15$ in the ^{166}Yb case.

Theoretical calculations in the framework of the many-BCS-quasiparticles plus rotor model in the $(i_{13/2})^2$ valence space yield energies along the ground-state band and the S-band which agree quite well with the experimental values. Moreover, the calculations are able to reproduce the observed branchings from states of the ground-state band and the S-band.

The cranking model analyses along the lines of refs.^{7,8)} give the crossing frequency $\hbar\omega_c$ between the g.s.b. and the S-band as ≈ 0.28 MeV. The adjusted values of the moment of inertia parameters give an alignment $i_x \approx 8\hbar$ for the S-band. The g.s.b. is found to upbend at $\hbar\omega \approx 0.35$ MeV, due to the crossing with the S' band in the particle-rotor model.

3.3. Paper III

The experiments described in paper III have led to the identification of very high-spin states in $^{165,167}\text{Yb}$. The ground-state bands based on the $[523] 5/2^-$ Nilsson orbital have been identified up to spins $53/2^-$ and $49/2^-$ for ^{165}Yb and ^{167}Yb , respectively, thereby extending the knowledge of the $(-,+)_1$ bands to well above the backbending region. The other signature of the $[523] 5/2^-$ band, i.e., the $(-,-)_1$ band, has been identified in the case of ^{165}Yb above the backbending. The favoured and the unfavoured members of the $i_{13/2}$ band have been established to quite high spin values, $49/2^+$ and $39/2^+$ for ^{165}Yb and $53/2^+$ and $43/2^+$ for ^{167}Yb , respectively.

This study can be regarded as a test case for the Cranked Shell Model in a region of stable deformation. A detailed and systematic comparison of the theoretical results with the experimental ones would tell us about the validity of that theoretical approach and/or of the underlying assumptions and approximations. Each rotational band is characterized by its Routhian (Hamiltonian in the rotating frame) and its alignment, and these two quantities carry the fingerprints of the quasiparticle configurations that form the basis of that band. These are the quantities that can be directly compared with those from CSM calculations.

A problem, that arises while transforming the experimental data to quantities in the rotating frame, concerns the choice of the reference frames and their moment of inertia parameters. The $\mathcal{J}_1 = 90 \text{ MeV}^{-3} \hbar^4$ value used throughout this paper is a compromise between different choices, and a detailed systematic investigation of the VMI parameters (ref. 18) justify such a choice for stable deformation around $N \sim 96$.

Routhians and alignments have been extracted from the experimental data for the nuclei $^{165,166,167}\text{Yb}$. Experimental single-quasineutron Routhians have been used to construct two- and three-quasineutron Routhians. While comparing the constructed multi-quasineutron Routhians with the experimental ones, the constructed Routhians have been shifted, to compensate for the effects of the interaction between the quasineutrons, originating mainly from the reduction of Δ_n due to the blocking of the pairing contributions by the unpaired quasineutrons. The agreement between the experimental and the

constructed Routhians in ^{166}Yb suggest the residual interaction between the two unpaired quasineutrons to be weakly dependent on frequency or configuration. These comparisons furthermore suggest the residual interaction between the two quasineutrons to be about 300 keV.

The experimental alignments of the three-quasineutron configurations, $(-,+)_1^3$ and $(-,-)_1^3$, turn out to be somewhat smaller than those from either the sum of the experimental one-quasiparticle alignments, or those from the CSM calculations using Δ_n values that reproduce the correct crossing frequency in the $(-,+)_1$ bands. This is in accordance with the expectations, since the decrease in the pairing correlation parameter Δ_n in seniority-three configurations compared to seniority-one configurations would imply a decrease in alignments in the three-quasineutron configurations in the CSM calculations.

The signature splitting between the $(-,+)_1$ and the $(-,-)_1$ bands in ^{165}Yb are accounted for by the CSM calculations. (The neutron pairing-correlation parameter Δ_n has been adjusted in the calculations to reproduce the correct crossing frequency of the $(-,+)_1$ band. See further the discussion of paper IV). The CSM calculations, however, fail to account for either the signature splitting or the crossing frequencies in the $(+,+)_1$ and the $(+,-)_1$ bands in ^{165}Yb . One source of these discrepancies may be associated with the interactions of these configurations with other positive-parity single-quasineutron configurations distant from the Fermi surface. Moreover, recent calculations suggest the value of the

pairing-gap parameter in the $i_{13/2}$ bands in the rare-earth nuclei to be somewhat larger than that in the negative-parity bands. Although such changes in the value of Δ_n would shift the crossing frequency in the CSM calculations in the right direction, the observed signature splitting in the $i_{13/2}$ band still remains an open question.

It has recently been pointed out (ref. 19) that the $B(M1)$ and the $B(E2)$ values for transitions between the two bands with different signatures and based on the same high-j orbit are strongly perturbed by rotation. The experimental values extracted for such transitions between the favoured and the unfavoured sequence of states based on the $i_{13/2}$ neutron orbital in $^{165,167}\text{Yb}$ adduce to such a perturbative effect of rotation on the $B(M1)$ and $B(E2)$ transition matrix elements.

3.4. Paper IV

A systematic investigation of high-spin states in deformed nuclei and a detailed comparison with theory should give rise to a number of unsolved problems. Paper IV deals with one such problem.

In even-even rare-earth nuclei, the alignment of a pair of $i_{13/2}$ quasineutrons gives rise to the crossing of the ground-state band by the S-band. The alignment of the same pair of quasineutrons should give rise to the lowest-frequency band crossing in the negative-parity bands in the neighbouring odd-N nuclei, where the alignment of this pair of quasineutrons is not blocked by the presence of the unpaired quasineutron. A study of the lowest-frequency band crossings in $N=90-102$

nuclei show that the crossing frequencies for the first crossing in the negative-parity bands in odd-N nuclei are systematically lower than those for the ground-state bands in even-N nuclei. The reproduction of odd-even effect in the Cranked Shell Model invokes the use of such values of Δ_n , the neutron pairing-correlation parameter, for odd-N nuclei, that are systematically lower than those used for even-N nuclei. The first pair of the $i_{13/2}$ quasineutrons in these nuclei lie close to the Fermi surface, and the neutron pairing-correlation parameter is a decisive factor governing their distance from the Fermi surface and hence the band crossing frequencies. This means that a reduction in pairing should lower the crossing frequency corresponding to the lowest-frequency band crossing. This is in accordance with the expectations for odd-N nuclei, where the presence of one unpaired quasineutron should reduce the pairing-correlation parameter due to blocking effects.

The value of Δ_n extracted from the band crossing frequencies are, however, parameters used in CSM calculations. A detailed comparison of the Δ_n values extracted in such a way for the even-even nuclei with those obtained from odd-even mass differences indicate the possibility of obtaining quantitative information on Δ_n from the crossing frequencies.

Acknowledgements

I wish to express my sincere gratitude to my supervisor Professor Hans Ryde, who has introduced me to the world of high-spin phenomena and has guided me throughout the course of this study.

This study would not have been possible without a fruitful and vigorous collaboration between theoreticians and experimentalists. I want to express my sincere gratitude to all my collaborators from different parts of the world, who have taken part in this study, for their constructive criticisms, fruitful discussions and a pleasant and inspiring collaboration. I would also like to thank the accelerator staff at the different laboratories, where the experiments were conducted, for their hard work in getting the beams on to the targets.

Finally, I would like to thank the colleagues at the Department of Physics, Lund for providing me with a happy environment to work in.

References

- 1) S. Cohen, F. Plasil and W.J. Swiatecki, *Annals of Physics*, 82 (1974) 557
- 2) M. Blann, University of Rochester Report Nos. UR-MSRL-159 and C00-3494-34
- 3) D.L. Hillis, J.D. Garrett, O. Christensen, B. Fernandez, G.B. Hagemann, B. Herskind, B.B. Back and F. Folkmann, *Nucl. Phys.* A325 (1979) 216
- 4) J.D. Garrett and B. Herskind, *Proc. of the Daresbury Study Weekend*, Sept. 22-23 (1979) p30; and B. Herskind, *J. de Physique (colloque)* C10 (1980) 106
- 5) F.S. Stephens and R.S. Simon, *Nucl. Phys.* A183 (1972) 257
- 6) A. Johnson, H. Ryde and J. Sztarkier, *Phys. Lett.* B34 (1971) 605
- 7) Aa. Bohr and B.R. Mottelson, *J. Phys. Soc. Japan* 44 (1978) Suppl. p157
- 8) R. Bengtsson and S. Frauendorf, *Nucl. Phys.* A314 (1979) 27;
R. Bengtsson and S. Frauendorf, *Nucl. Phys.* A327 (1979) 139
- 9) Aa. Bohr and B.R. Mottelson, *Physics Today*, June 1979, p25
- 10) Aa. Bohr and B.R. Mottelson, *Physica Scripta*, 10A (1974) 13
- 11) J. Pedersen, B.B. Bach, F.M. Bernthal, S. Bjørnholm, J. Borggren, O. Christensen, F. Folkmann, B. Herskind, T.L. Khoo, M. Neimann, F. Pühlhofer and G. Sletten, *Phys. Rev. Lett.* 39 (1977) 990
- 12) P. Kleinheinz, *Proc. Symp. on High Spin Phenomena in Nuclei*, Argonne (1979), ANL/PHY-79-4, p125
- 13) C.G. Andersson, G. Hellström, G. Leander, I. Ragnarsson, S. Aberg, J. Krumlinde, S.G. Nilsson and Z. Szymanski, *Nucl. Phys.* A309 (1978) 141 ; and T. Døssing, K. Neergård, K. Matsuyanagi and H.C. Chang, *Phys. Rev. Lett.* 39 (1977)

1395

- 14) J. Blomquist, Proc. Symp. on High Spin Phenomena in Nuclei, Argonne (1979), ANL/PHY-79-4, p155
- 15) I. Bergström, Proc. of XVI Int. Winter Meeting on Nuclear Physics, Bormio, Jan. 16-21 (1978), p636
- 16) A. de-Shalit and I. Talmi, Nuclear Shell Theory, Academic Press (1963)
- 17) J. Blomquist, P. Kleinheinz, R. Broda and P.J. Daly, Zeit. Phys. (to be published)
- 18) J.D. Garrett, Proc. of the XIV Summer School on Nuclear Physics, Mikolajki (Poland), Aug. 31- Sept. 12 (1981), to be published in Nukleonika
- 19) I. Hamamoto, Phys. Lett. 102B (1981) 225 ; and I. Hamamoto, NORDITA preprint 81/39

High Spin Shell Model Excitations in ^{149}Gd

M. Piiparinen*, R. Pengo, Y. Nagai**, E. Hammarén***, and P. Kleinheinz
Institut für Kernphysik, Kernforschungsanlage Jülich, Federal Republic of Germany

N. Roy, L. Carlén, and H. Ryde
Department of Physics, University of Lund, Sweden

Th. Lindblad, A. Johnson, S.A. Hjorth, and J. Blomqvist
Research Institute of Physics, Stockholm, Sweden

Received January 19, 1981

The high spin level structure of the three-neutron nucleus ^{149}Gd has been investigated by in-beam γ -ray and electron spectroscopy with (α, xn) reactions. The observed levels are characterized as members of the shell model multiplets $\nu f_{7/2}^3$, $\nu h_{9/2} f_{7/2}^2$, $\nu f_{7/2}^3 \times 3^-$, $\nu h_{9/2} f_{7/2}^2 \times 3^-$, and tentatively $\nu f_{7/2}^3 \times (3^-)^2$. The energies of the $\nu f_{7/2}^3$ states agree only moderately with those calculated using empirical two-nucleon interactions taken from ^{148}Gd , which indicates the importance of long range contributions already at $N=85$.

1. Introduction

In a number of recent studies of the high spin states in nuclei around ^{146}Gd it has been shown [1–4] that this nucleus can act as a doubly closed core. This means that its yrast levels and those of other nuclei in this region can be described using techniques based on the spherical shell model similar to those which have been successfully applied in the ^{208}Pb region [5]. In the present study we have investigated the high spin levels in the ^{149}Gd nucleus which has three neutrons outside the ^{146}Gd core. From previous investigations [1, 6] the high spin states in the one- and two-neutron nuclei ^{147}Gd and ^{148}Gd are fairly well known. From this experimental information it should be possible – using the shell model – to calculate the high spin excitations for the three-neutron nucleus ^{149}Gd provided that the relevant ground state masses are known. On the other hand, the Gd isotopes with $N \geq 89$ are known to be strongly deformed, and deformed configurations

have been identified [7] in ^{151}Gd and other $N=87$ nuclei. A study of ^{149}Gd is therefore of interest since it will show to what extent the spherical shell model can describe the $N=85$ nuclei.

Of particular interest in this region are the octupole excitations, which at $N \approx 82$ are lowest for Gd since here the Fermi energy lies between the $d_{5/2}$ and $h_{11/2}$ proton orbits. When more neutrons are added $\nu f_{7/2} i_{13/2}$ transitions will add to the octupole strength and further lower its energy. This unusually low octupole energy favours the observation of two-phonon octupole excitations; in ^{147}Gd a $19/2^-$ state has been suggested [1] to be predominantly of $\nu f_{7/2} \times 3^- \times 3^-$ character. In the present study we have identified a group of levels in ^{149}Gd which might be associated with an analogous $\nu f_{7/2}^3 \times 3^- \times 3^-$ excitation.

The energy levels of ^{149}Gd have previously been investigated in β -decay [8–10] of ^{149}Tb and $^{149\text{m}}\text{Tb}$, but only few of the states observed in these studies are also populated in the present in-beam experiments. In an earlier $(\alpha, 3n)$ study [11] a few high-spin states associated with the $13/2^+$ level at

* Alexander von Humboldt fellow 1978–80. On leave from University of Jyväskylä, Finland

** On leave from Osaka University, Japan

*** Visitor from University of Jyväskylä, Finland

956 keV have been reported. After completion of our measurements we have become aware of an independent in-beam study of ^{149}Gd , with the $(\alpha, 2n)$ and $(^{11}\text{B}, 3n)$ reactions, which is reported [12] in a recent annual report. The level scheme of that work in many aspects agrees with our own results which have previously been reported in [13 and 14].

2. Experiments

In the present work we have investigated the ^{149}Gd nucleus by in-beam γ - and electron-spectroscopy using the $(\alpha, 3n)$, $(\alpha, 4n)$, and $(\alpha, 5n)$ reactions. The $(\alpha, 3n)$ and $(\alpha, 5n)$ experiments were carried out at the cyclotron at Jülich with beam energies of

Table 1. Gamma transitions in ^{149}Gd observed in the $^{150}\text{Sm}(\alpha, 5n)$ reaction at 67 MeV bombarding energy

E_γ (keV)	Rel. γ -ray intensity ^a	Ang. distr. coeff. ^b		P^c	Placement	
		A_2	A_4		E_i (keV)	$I_i^\pi \rightarrow I_f^\pi$
77.6(1)	178	-0.20(2)	-0.04(3)		873.5	$11/2^+ \rightarrow 9/2^-$
82.5(1)	101	-0.28(3)	-0.05(4)		956.0	$13/2^+ \rightarrow 11/2^+$
98.2(1)	177	0.31(1)	-0.00(1)		873.5	$11/2^- \rightarrow 11/2^-$
159.6(1)	90	0.28(1)	-0.06(2)		3,387.5	$27/2^- \rightarrow 23/2^+$
165.1(3)	25	0.10(3)	0.01(4)		165.1	$5/2^- \rightarrow 7/2^-$
180.6(1)	129	-0.23(1)	-0.01(1)		956.0	$13/2^+ \rightarrow 11/2^-$
245.1(2)	28	0.33(4)	0.03(6)		3,632.6	$27/2^- \rightarrow 27/2^+$
248.1(3)	107 ^d	-0.15(1) ^d	0.00(2) ^d		4,572.4	$(31/2^-) \rightarrow (29/2^-)$
292.5(3)	48	0.32(2)	-0.09(3)		2,524.3	$21/2^- \rightarrow 17/2^-$
325.5(3)	25	-0.38(4)	-0.01(6)		2,383.8	$19/2^- \rightarrow 17/2^-$
337.8(2)	37	-0.38(3)	-0.04(5)		3,632.6	$27/2^+ \rightarrow 25/2^-$
378.2(3)	44	-0.14(3)	-0.01(4)		3,765.7	$29/2^- \rightarrow 27/2^+$
422.8(2)	64	-0.29(2)	0.02(3)			
449.0(2)	39	0.37(3)	-0.05(5)		2,058.3	$17/2^- \rightarrow 13/2^-$
454.9(2)	75	0.26(2)	-0.01(3)		2,856.6	$\rightarrow 21/2^+$
466.0(2)	217 ^e	0.31(2) ^e	-0.03(3) ^e	-0.08(4)	2,524.3	$21/2^- \rightarrow 17/2^-$
499.5(3)	78	0.33(2)	-0.00(3)			
528.0(1)	105	-0.23(2)	0.03(2)		1,484.1	$15/2^- \rightarrow 13/2^+$
574.2(1)	214	-0.21(1)	0.01(1)	0.12(3)	2,058.3	$17/2^- \rightarrow 15/2^-$
622.6(3)	30	0.01(6)	-0.02(8)		2,231.8	$17/2^- \rightarrow 13/2^-$
630.4(5)	$\sim 49^f$	0.23(3) ^f	-0.07(4) ^f		795.9	$9/2^- \rightarrow 5/2^-$
643.7(2)	45	-0.19(4)	-0.05(5)		2,383.8	$19/2^- \rightarrow 17/2^-$
661.4(1)	360	0.30(1)	-0.08(1)	-0.06(3)	2,401.7	$21/2^+ \rightarrow 17/2^+$
683.3(2)	36	-0.95(4)	-0.02(6)		3,085.0	$23/2^+ \rightarrow 21/2^+$
703.6(2)	101 ^g	-0.21(3) ^g	0.00(3) ^g	-0.08(9)	3,227.9	$23/2^+ \rightarrow 21/2^-$
708.8(1) ^h	344 ^h	0.34(1)	-0.06(1)	-0.09(3)	1,484.1	$15/2^- \rightarrow 11/2^-$
712.3(2)	79	0.39(2)	-0.10(3)		4,324.3	$(29/2^-) \rightarrow 25/2^-$
733.1(4)	35	-0.16(4)	-0.07(6)		3,134.8	$23/2^- \rightarrow 21/2^+$
747.5(5)	$\sim 39^i$	0.18(1) ⁱ	-0.02(2) ⁱ		2,231.8	$17/2^- \rightarrow 15/2^-$
750.8(5)	58	0.29(2)	-0.08(3)		3,134.8	$23/2^- \rightarrow 19/2^-$
775.3(1)	641	0.26(1)	-0.05(1)	-0.09(2)	775.3	$11/2^- \rightarrow 7/2^-$
784.3(3)	427 ^j	0.27(1)	-0.06(1)	-0.10(2)	1,740.3	$17/2^+ \rightarrow 13/2^+$
795.9(1)	334	0.07(1)	0.03(1)	0.16(5)	795.9	$9/2^- \rightarrow 7/2^-$
813.3(2)	48	0.22(4)	-0.08(5)		1,609.3	$13/2^- \rightarrow 9/2^-$
826.4(4)	16				3,227.9	$23/2^+ \rightarrow 21/2^+$
834.2(3)	37	-0.16(3)	-0.02(4)		1,609.3	$13/2^- \rightarrow 11/2^-$
863.0(4)	15	0.54(8)	0.14(12)		3,387.5	$27/2^+ \rightarrow 21/2^-$
893.2(1)	148	0.32(1)	-0.08(2)		3,294.9	$25/2^+ \rightarrow 21/2^+$
899.6(2)	44	0.28(3)	0.01(5)		2,383.8	$19/2^- \rightarrow 15/2^-$
1,087.7(1)	124	0.34(2)	-0.09(3)	-0.12(6)	3,612.0	$25/2^- \rightarrow 21/2^-$

^a Measured at $\theta=125^\circ$; error $\sim 5\%$, larger for weak or unresolved lines

^b Errors are pure fit errors

^c Counting rate asymmetry $P=(N_+ - N_-)/(N_+ + N_-)$. Polarization data measured with the $^{149}\text{Sm}(\alpha, 4n)$ reaction at 51 MeV

^d Data uncertain, not resolved from a degenerate background line

^e Data corrected for 6% contribution from 465.6 keV M1 transition in ^{148}Gd

^f Obscured by the strong 631.9 keV transition in ^{148}Gd

^g Data corrected for 28% contribution from 704.0 keV E2 transition in ^{150}Gd

^h Doublet; the weak component also belongs to ^{149}Gd but is not placed in the level scheme

ⁱ Obscured by the intense 747.2 keV line in ^{146}Sm . Intensity derived from coincidence data

^j Intensity corrected for 40% contribution from 784.5 keV E2 transition in ^{148}Gd

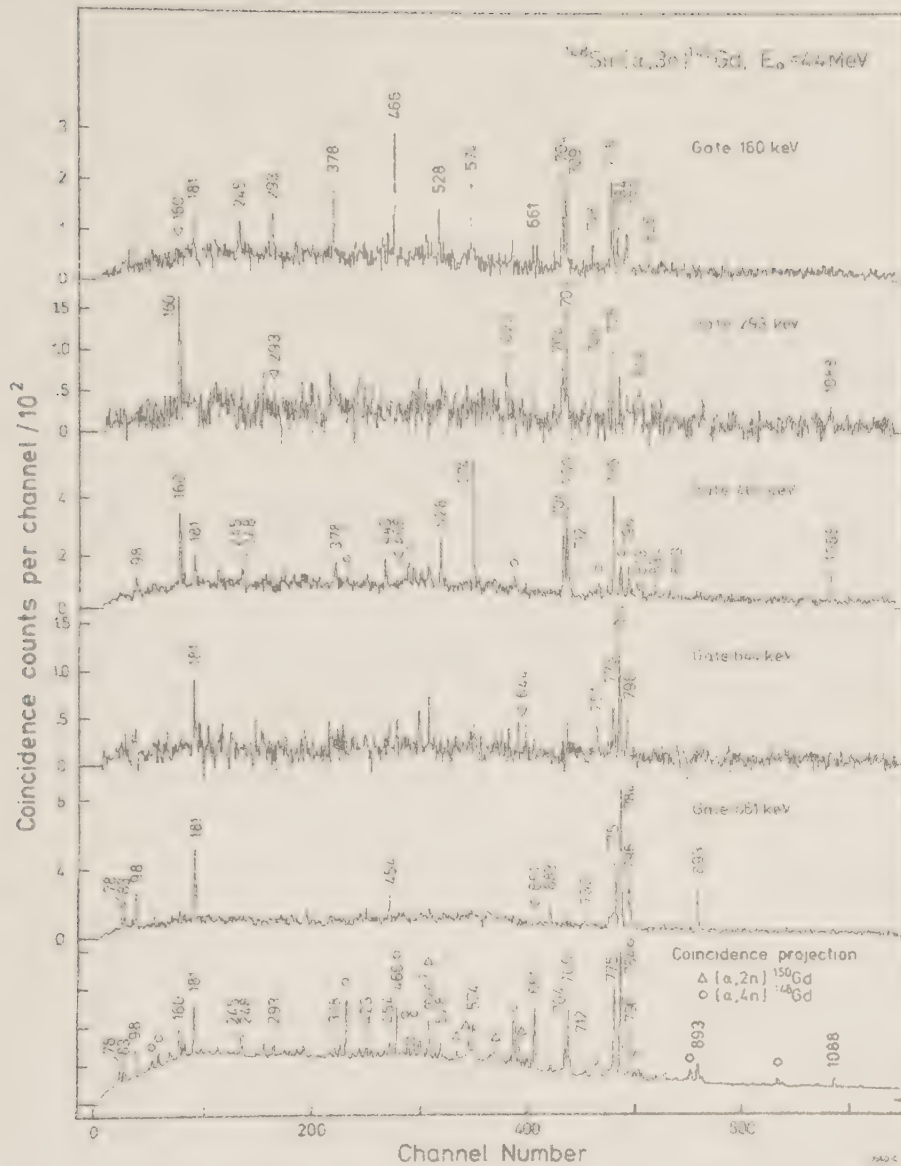
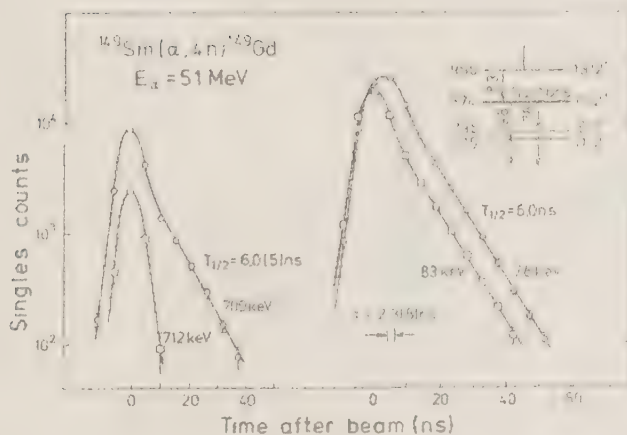


Fig. 2. Selected prompt coincidence spectra ($\Delta t_{\gamma\gamma} \approx 50$ ns) for ^{149}Gd measured during ± 20 ns intervals centered on the 140 ns separated beam bursts. The bottom spectrum shows the coincidence projection with no restriction on the two time parameters



3. Level Scheme and Spin-Parity Assignments

From atomic beam experiments [16] a ground state spin of $7/2$ has been determined for ^{149}Gd , and negative parity is inferred from the shell model.

The $T_{1/2} = 4.2$ min $^{149\text{m}}\text{Tb}$ isomer attributed [8] to the $\pi h_{11/2}$ configuration β -decays with $\log ft \approx 4.4$ to a level in ^{149}Gd at 796 keV, which therefore is char-

Fig. 3. Examples of t_{jRt} timing measurements for selected ^{149}Gd γ transitions. Both figures show the $T_{1/2} = 6.0$ ns half life; to the left a distribution of a prompt transition (712 keV) is included for comparison. The centroid shift extracted from the two curves to the right gives the $T_{1/2} = 1.6$ ns half life for the 874 keV level

acterized as $\nu h_{9/2}$ one particle excitation. This level is strongly populated in the present study. The level predominantly deexcites to the $\nu f_{7/2}$ ground state: a weak branch proceeds through a level at 165 keV, which from the β -decay of 4.2 h ^{149}Tb has been assigned [10] as $5/2^-$ state. The β -decay work has established numerous other levels, but they are not observed in our experiments.

The results of the measurements described in the preceding section establish the level scheme of Fig. 4. In most cases the angular distribution and polarization data, together with the observed branching ratios and $T_{1/2}$ limits, provide unambiguous spin and parity assignments. Intensity balance arguments have been used to determine the parity of the 874 keV level. The only possible multipolarities are $M1$ for the 83 keV feeding γ -ray, and $E1$ for the two 78 and 98 keV depopulating transitions. This gives positive parity for the 874 and 956 keV states. The dipole character of the 528 keV and 181 keV transitions requires $I^\pi=13/2^+$ for the latter state. In the previous section we have already discussed the multipolarity of the 704 keV line. It determines $I^\pi=23/2^+$ for the 3,228 keV state and, with the $E2$ character of the 160 keV isomeric transition, $I^\pi=27/2^+$ for the 6.0 ns isomer at 3,388 keV.

4. Discussion

4.1. The $\nu f_{7/2}^3$ States

The ^{149}Gd has three valence neutrons above the $N=82$ shell, and the $7/2$ ground state spin suggests its interpretation as $(\nu f_{7/2}^3)_{7/2}$ state. The $(f_{7/2}^3)_{11,2}$ and $(f_{7/2}^3)_{15/2}$ states at 775 and 1,484 keV are yrast states and are strongly populated in the present experiments. Of the non-yrast $f_{7/2}^3$ multiplet members one knows [10] the $5/2$ state at 165 keV. The 352 keV $3/2^-$ level seen [10] in the 4.2 h ^{149}Tb β decay most likely also belongs to the $\nu f_{7/2}^3$ configuration. Moreover, the $f_{7/2}^3$ multiplet contains a $9/2$ member which has not been observed. This state will be further discussed below.

Using angular momentum algebra [17] the energies of the $f_{7/2}^3$ multiplet members can be calculated from the empirical energies of the $f_{7/2}^2$ quartet as observed [6] in the two-particle nucleus ^{148}Gd . In Fig. 5 these calculated energies are compared with the experimental energy levels of ^{149}Gd . The absolute level energies are evaluated using the mass parameter

$$E_0 = M(^{146}\text{Gd}) - 3M(^{147}\text{Gd}) + 3M(^{148}\text{Gd}) - M(^{149}\text{Gd}) = -3,571 \text{ keV.} \quad (1)$$

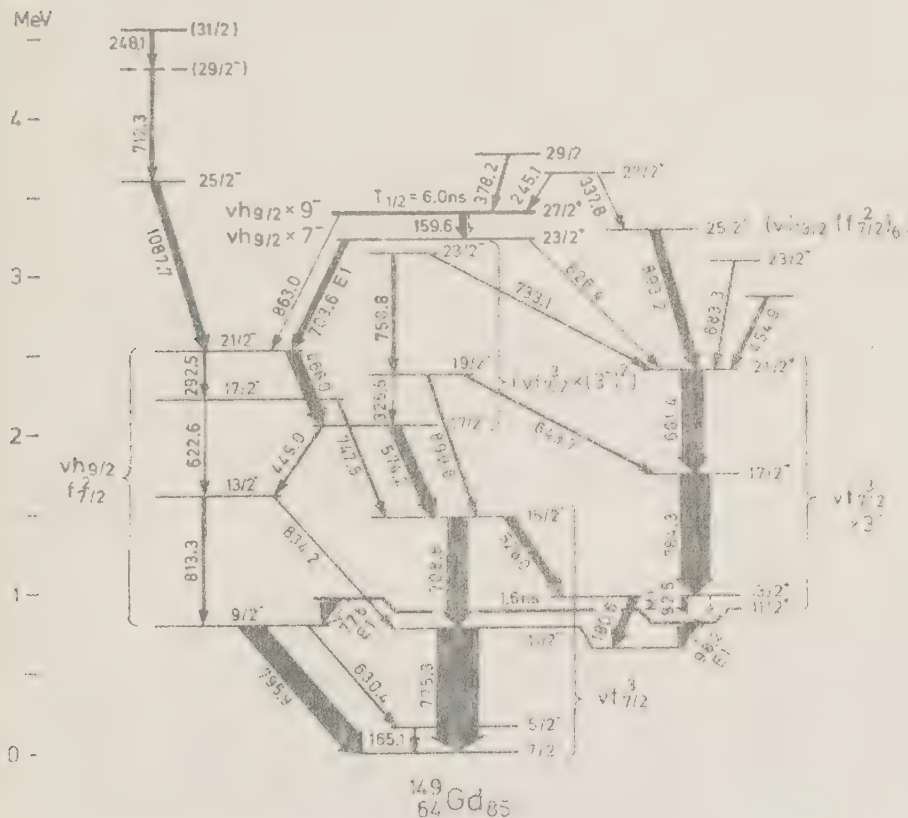


Fig. 4. Level scheme of ^{149}Gd established from the present in beam γ -ray studies. Transition intensities are drawn as observed in the $(\alpha, 5n)$ reaction, and multipolarities are given where conversion electron information is available. Proposed shell model configuration assignments are indicated

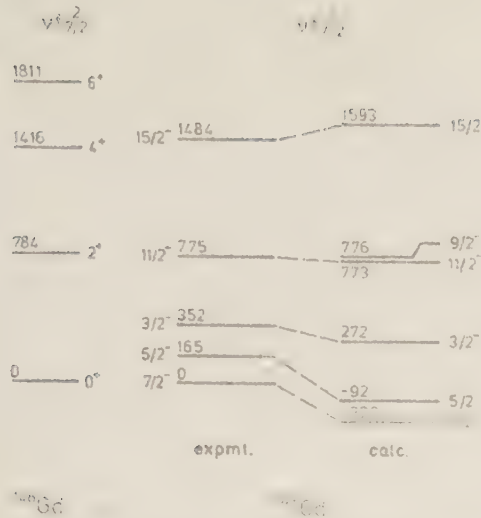


Fig. 5. Energies of the ^{149}Gd $\nu f_{7/2}^3$ states compared to the values calculated from the $\nu f_{7/2}^2$ states observed in the two-neutron nucleus ^{148}Gd

The mass values of the four nuclei are obtained from the 1977 mass tables [18] and from a recent analysis [19] of ground state masses in the ^{146}Gd region.

The agreement between calculated and experimental level energies is only moderate, even for the yrast multiplet members, which should be rather pure $f_{7/2}^3$ states. A similar calculation of the $\pi h_{9/2}^3$ levels [20] in ^{211}At agrees with experiment within 20 keV, and the level spacings calculated for the $\pi h_{11/2}^3$ yrast states in ^{149}Ho reproduce the experimental values [21] to $\lesssim 60$ keV. The comparison in Fig. 5 thus indicates that the shell model is no longer applicable here for accurate level energy calculations. This is in accord with the finding [19] that the $Z=64$ gap decreases rapidly when going from $N=82$ towards higher neutron number. At $N=86$ it has almost disappeared, and one therefore expects that quadrupole effects will significantly distort the $f_{7/2}^3$ energy spectrum. Nevertheless, the spherical shell model is still quite useful to describe the level spacings qualitatively.

4.2. The $\nu h_{9/2}$ Excitation and $\nu h_{9/2} f_{7/2}^2$ States

As we have mentioned in Sect. 3 the β decay data characterize [8] the 796 keV $9/2^-$ state as a $\nu h_{9/2}$ single-particle excitation. Similar β decay results have identified [22] the $\nu h_{9/2}$ state in ^{151}Dy at 527 keV. In the lighter isotones the $\nu h_{9/2}$ excitation is known from single neutron transfer experiments,

at 809 keV in ^{147}Sm [23], at 747 keV in ^{145}Nd [24], and at 668 keV in ^{143}Ce [25].

Additional support for the $\nu h_{9/2}$ interpretation comes from the γ decay data. The 796 keV state decays by $\gtrsim 90\%$ to the $(\nu f_{7/2}^3)_{7/2}$ ground state, whereas a $(\nu f_{7/2}^3)_{9/2}$ level, also expected at ~ 0.8 MeV, should predominantly decay by an E2 transition to the $(\nu f_{7/2}^3)_{5/2}$ level at 165 keV. The fact that only the 796 keV level is observed in ^{149}mTb β decay indicates that the two $9/2^-$ levels are not strongly admixed. The very detailed study [10] of 4.2 h ^{149}Tb β decay has established a level at 1,086 keV with $I=5/2, 7/2$, or $9/2$ and negative parity which could be the missing $(\nu f_{7/2}^3)_{9/2}$ state.

With one valence neutron lifted to the $h_{9/2}$ orbital the two remaining $f_{7/2}$ neutrons can form the characteristic $(\nu f_{7/2}^2)_{0^+, 2^+, 4^+, 6^+}$ multiplet, giving rise to yrast levels with $I^\pi=9/2^-, 13/2^-, 17/2^-$, and $21/2^-$ which are all observed in the four isotones ^{147}Sm [26], ^{149}Gd , ^{151}Dy [27], and ^{153}Er [28]. The situation is somewhat complicated in ^{149}Gd since here two $17/2^-$ states are found, at 2,058 keV and 2,232 keV excitation. The complete $\nu h_{9/2} f_{7/2}^2$ multiplet contains in fact two $17/2^-$ levels, but one of them is expected to lie definitely above the $21/2^-$ member at 2,524 keV and therefore cannot be identified with one of the two observed $17/2^-$ levels. The measured γ -ray branchings indicate that the observed two $17/2^-$ levels are rather mixed, but we interpret the 2,232 keV state to have mainly $(\nu h_{9/2} f_{7/2}^2)_{17/2}$ character. Two arguments suggest this choice: Firstly, the 293 keV E2 transition is 2.3 times faster than the 466 keV transition, favouring the former as the intramultiplet transition. Secondly, we have compared the $(M1, 17/2^- \rightarrow 15/2^-)/(E2, 17/2^- \rightarrow 13/2^-)$ branching ratios for the two $17/2^-$ states to the values found [26, 27] in ^{147}Sm and ^{151}Dy where only one $17/2^-$ has been observed. The energy-corrected $M1/E2$ transition intensity ratios in ^{147}Sm and ^{151}Dy are 0.37(4) and 0.38(4) which compare well with the value 0.33(15) obtained for the upper $17/2^-$ state in ^{149}Gd , whereas the ratio for the lower $17/2^-$ state is 0.60(8). Finally, one would expect the $21/2^-$ to $17/2^-$ spacing of the $\nu h_{9/2} f_{7/2}^2$ multiplet to be smaller than the 6^+ to 4^+ separation of the $\nu f_{7/2}^2$ multiplet as observed in ^{148}Gd . This also favours assignment of the higherlying $17/2^-$ state as $(\nu h_{9/2} f_{7/2}^2)_{17/2}$.

To calculate the complete $\nu h_{9/2} f_{7/2}^2$ multiplet one would need empirical $\nu h_{9/2} f_{7/2}$ interaction energies for all possible spin values of this two-neutron multiplet. However, in ^{148}Gd only the 8^+ member is known [6]. Assuming that the $(\nu h_{9/2} f_{7/2})_7$ interaction is about 0.3 MeV less attractive than the 8^+ interaction we can calculate the excitation energy of

the $21/2^-$ state in ^{149}Gd as

$$E_x((h_{9/2}f_{7/2}^2)_{21/2}) = E_x((f_{7/2}^2)_6) + 1.44 E_x((h_{9/2}f_{7/2})_8) \\ + 0.56 E_x((h_{9/2}f_{7/2})_7) - E_x(h_{9/2}) + E_0 \simeq 2.40 \text{ MeV}$$

which is in rather good agreement with the experimental excitation energy of 2.524 MeV. Here, E_0 is the same mass parameter as in (1), and the excitation energies for the two-neutron configurations are taken from ^{148}Gd . $E_x(h_{9/2}) = 1.398 \text{ keV}$ is the energy [29] of the $vh_{9/2}$ level in ^{147}Gd . The second and third terms give the contribution of the $vh_{9/2}f_{7/2}$ residual interaction to the $21/2^-$ energy; the numerical factors are angular momentum recoupling coefficients.

4.3. The $27/2^+$ 6.0 ns Isomer at 3,388 keV

In ^{148}Gd a 9^- isomer with 17.5 ns half life at 2,695 keV has been interpreted [6] as the $(3^- \times (vf_{7/2}^2)_6)_9$ state, probably with a large $(vf_{7/2}i_{13/2})_9$ admixture. In ^{149}Gd , with the third valence neutron placed in the $h_{9/2}$ orbit, an analogous $27/2^+$ state can be formed. Since the $27/2^+$ isomer in ^{149}Gd decays in a similar manner as the ^{148}Gd 9^- level we interpret it as the $vh_{9/2} \times 9^-$ configuration. Its excitation energy, 863 keV above the $(vh_{9/2}(f_{7/2}^2)_6)_{21/2}$ state, also supports this suggestion as the corresponding $(vf_{7/2}^2)_6$ to 9^- energy separation in ^{148}Gd is 884 keV. The $23/2^+$ level at 3,228 keV is assigned as $vh_{9/2} \times 7^-$.

In the decay of the 6 ns isomer we observe the $27/2^+ \rightarrow 21/2^-$ $E3$ transition, analogous to the $9^- \rightarrow 6^+$ $E3$ transition [6] in ^{148}Gd . The half life and the decay branching ratio give

$$B(E3, 27/2^+ \rightarrow 21/2^-) = 44 \pm 11 \text{ W.U.}$$

This result compares with the $B(E3)$ values measured in ^{148}Gd and ^{147}Gd , $55 \pm 6 \text{ W.U.}$ [6] and $44 \pm 6 \text{ W.U.}$ [1]. Thus all Gd $B(E3)$ values at $N > 82$ are larger than the $37 \pm 4 \text{ W.U.}$ measured [30] for the ^{146}Gd core.

The isomeric 160 keV $E2$ transition has a $B(E2)$ value of

$$B(E2, 27/2^- \rightarrow 23/2^+) = 12 \pm 1 \text{ W.U.}$$

In our interpretation this γ -ray is essentially a $vf_{7/2}^2 6^+ \rightarrow 4^+$ transition, although other configurations are expected to contribute to the $27/2^+$ and $23/2^+$ levels. Analogous isomeric $E2$ transitions have been observed in a number of neighbouring nuclei, and have been analyzed to determine an approximate value for the neutron effective $E2$ transition

charge. For ^{149}Gd we obtain

$$e_{\text{eff}} = 4.0 \pm 0.2$$

This should be compared to the value of $2.7 \pm 0.1 e$ extracted from the analogous $9^- \rightarrow 7^-$ transition [6] in ^{148}Gd , and is in agreement with the systematics [31] of neutron e_{eff} values found for other $N=84$ and $N=85$ nuclei.

4.4. The $vf_{7/2}^3 \times 3^-$ States

In Sect. 3 we discussed the $I^\pi = 13/2^+$ assignment for the 956 keV level. This $13/2^+$ state is in nice accord with the isotonic systematics; $13/2^+$ states at similar energies have been identified in ^{153}Er ($E_x = 971 \text{ keV}$) [28], ^{151}Dy (968 keV) [27], ^{147}Sm (1,031 keV) [23, 26], ^{145}Nd (1,112 keV) [24], and probably also in ^{143}Ce (1,221 keV) [25]. In the latter three cases these states are populated with $l=6$ in single neutron transfer which indicates that the $vi_{13/2}$ single-particle excitation contributes strongly to them.

It has recently been argued [3] that the 1.6 MeV ^{146}Gd core octupole state lies lower in energy than the unperturbed $vi_{13/2}$ single-particle excitation in the $N=83$ nucleus ^{147}Gd . This suggests that the 997 keV $13/2^+$ state in ^{147}Gd , and probably also the 956 keV $13/2^+$ level in ^{149}Gd , are predominantly $vf_{7/2} \times 3^-$ excitations rather than $vi_{13/2}$ single particle states, although one expects the two configurations to be strongly admixed.

The present data support this $vf_{7/2}^3 \times 3^-$ interpretation for the 956 keV level in ^{149}Gd . If the $vi_{13/2}$ single-particle excitation were dominant one would expect to observe a $(vf_{7/2}^2)0, 2, 4, 6$ multiplet on top of the $13/2^+$ level. In contrast, we find the characteristic $vf_{7/2}^3$ multiplet associated with the $13/2^+$ state, which further points to the prevalent octupole character for that level. In the present work we have found four members of the $vf_{7/2}^3 \times 3^-$ multiplet, with spins $11/2^+$, $13/2^+$, $17/2^+$, and $21/2^+$. In a very recent study [12] the 874 keV state has been assigned as $11/2^-$ and an associated level at 1,751 keV as $15/2^-$. If these levels are reassigned to positive parity the 1,751 keV state could well be the $((vf_{7/2}^3)_{9/2} \times 3^-)_{15/2}$ multiplet member in analogy to a similar $15/2^{(+)}$ level [25] at 1,762 keV in ^{147}Sm .

An apparent difference between the ground state $f_{7/2}^3$ multiplet and the $vf_{7/2}^3 \times 3^-$ multiplet is the much lower relative energy of the $(vf_{7/2}^3)_{5/2}$ multiplet member in the latter case. In general the large negative quadrupole moment in a $(f^3)_{j-1}$ configuration gives rise to a lowering of the energy through the quadrupole interaction. The interaction with the predo-

minant $(\pi d_{5/2}^{-1} h_{11/2}) 3^-$ octupole configuration will further lower this $5/2^-$ state, thus giving rise to the $11/2^+$ level at 874 keV in ^{149}Gd , 83 keV below the $13/2^+$ state. A similar lowering of the $(\nu f_{7/2}^3)_{5/2}$ energy has also been established in other $N=85$ nuclei. In ^{147}Sm [26] and ^{150}Tb [32] the $\nu f_{7/2}^3$ multiplet associated with the octupole excitation has the same level ordering with the $5/2$ member respectively 99 keV and 42 keV below the $7/2$ member, and the $(\pi h_{11/2}^2 (\nu f_{7/2}^3)_{5/2}) 25/2^-$ state in ^{151}Dy [27] lies 47 keV below the associated $27/2^-$ state.

4.5. Higher-Lying Positive-Parity States

The experiments have established a number of additional positive parity states above 3 MeV which might involve the $\nu i_{13/2}$ orbital. However, negative parity states of proton particle-hole character occur [6] at $E_x \geq 3$ MeV in the yrast line of ^{148}Gd , which makes characterization of positive parity levels in ^{149}Gd in this region rather uncertain and prevents configuration assignments for higher-lying states. The strongly populated $25/2^-$ state at 3,295 keV may be the $\nu i_{13/2} f_{7/2}^2$ state with maximum spin alignment which cannot mix with the $\nu f_{7/2}^3 \times 3^-$ multiplet. The energy of that state can in principle be calculated as

$$\begin{aligned} E_x((i_{13/2} f_{7/2}^2)_{25/2}) \\ = E_x((f_{7/2}^2)_{10}) + 2 \times 1 E_x((f_{7/2} i_{13/2})_{10}) \\ + E_x(i_{13/2}) + E_0 \end{aligned}$$

where in this case the mass parameter [18, 19] is

$$\begin{aligned} E_0 = -M(^{146}\text{Gd}) + M(^{147}\text{Gd}) + M(^{148}\text{Gd}) \\ - M(^{149}\text{Gd}) = -537 \text{ keV}. \end{aligned}$$

The first term is the excitation energy of the $(\nu f_{7/2}^2) 6^+$ state in ^{148}Gd . The $\nu f_{7/2} i_{13/2}$ residual interaction ΔE for $I=10,9$ is expected to be smaller than ~ 0.1 MeV and is neglected here. The third term is the unperturbed $\nu i_{13/2}$ single-particle energy. This energy is an important quantity for yrast level calculations in this region, but unfortunately it is not well known from the spectrum of ^{147}Gd . We therefore can estimate it from the above equation. The result

$$\varepsilon(i_{13/2}) - \varepsilon(f_{7/2}) = 2.0(1) \text{ MeV}$$

supports the earlier [3] contention that the $i_{13/2}$ single-neutron state lies higher than the 1.6 MeV octupole excitation of ^{146}Gd . It also agrees with a similar indirect estimate ($\varepsilon(i_{13/2}) \gtrsim 2$ MeV) obtained [6] from the ^{148}Gd yrast level spectrum. The

± 0.1 MeV uncertainty in $\varepsilon(i_{13/2})$ derives from the neglect of the residual interaction only. It is difficult to estimate a more realistic uncertainty since as we have pointed out it is not quite clear whether the spherical shell model at $N=85$ can be applied in a quantitative manner.

The same considerations are valid for the $23/2^+$ member of the $\nu i_{13/2} f_{7/2}^2$ multiplet, which is also free of $\nu f_{7/2}^3 \times 3^-$ admixtures. The $23/2^+$ level at 3,085 keV could possibly be this excitation.

4.6. The Negative-Parity Levels at 2,058, 2,384, and 3,135 keV

For essentially all levels below 3 MeV shown in Fig. 4 it is possible to give reasonably firm structure interpretations as discussed in the preceding sections. The only exceptions are the very low-lying $17/2^-$ level at 2,058 keV mentioned in Sect. 4.2, and two additional negative parity states with $I=19/2$ and $23/2$ at 2,384 and 3,135 keV. We have previously argued that the $17/2^-$ state cannot be the expected second $17/2$ member of the $\nu h_{9/2} f_{7/2}^2$ multiplet. The same argument is valid for the 2,384 keV $19/2^-$ state, since the $(\nu h_{9/2} f_{7/2}^2)_{19/2}$ level should also lie higher than the $21/2^-$ multiplet member. It is difficult to form such $17/2^-$ or $19/2^-$ states at this low excitation energy from the three valence neutrons. On the other hand, the observed levels also lie too low to involve more complex particle-core excitations.

A possible interpretation for the 2,384 keV $19/2^-$ level is to attribute it to a $(3^- \times 3^-) 6^+$ two-phonon octupole excitation built on the ground state. The $17/2^-$ and $23/2^-$ levels, accordingly, would correspond to the $5/2^-$ and $11/2^-$ members of the $\nu f_{7/2}^3$ multiplet. This interpretation is indicated on the level scheme of Fig. 4. The $19/2$ to $17/2$ energy separation is here as large as 326 keV. One would indeed expect an additional lowering of the $(\nu f_{7/2}^3)_{5/2}$ state in the case of two phonons, and when comparing the $5/2$ to $7/2$ energy separation in the three multiplets $\nu f_{7/2}^3$, $\nu f_{7/2}^3 \times 3^-$, and $\nu f_{7/2}^3 \times 3^- \times 3^-$ one notices as expected a regular behaviour for the energy lowering of the $5/2$ state.

In quite similar (α, xn) in-beam studies [26, 27] of the neighbouring $N=85$ isotones ^{151}Dy and ^{147}Sm no analogous low-lying negative parity levels are found. This is in accord with our interpretation of the ^{149}Gd states, since it is well known, from the even mass $N=82$ to 86 level systematics that the octupole excitation is lowest in Gd. Similarly, in the odd A nuclei with $N=83$ and $N=85$, the first $13/2^-$

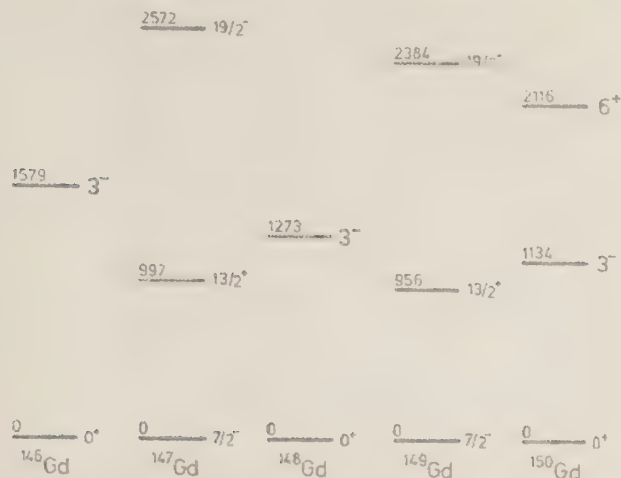


Fig. 6. Octupole states and tentative two-phonon octupole states in Gd nuclei with $N \geq 82$

excitation, which is of predominant $\nu f_{7/2} \times 3^-$ character, is also lowest in Gd.

Candidates for two-phonon octupole excitations exist also in other Gd isotopes. In the $N=83$ nucleus ^{147}Gd a $19/2^-$ level at 2,572 keV decays [1] through an $E3$ transition to the 997 keV $13/2^+$ level of mostly $[3] \nu f_{7/2} \times 3^-$ character. It has been argued [1] that this $19/2^-$ state has a large $\nu f_{7/2} \times 3^- \times 3^-$ component, since also in this case it is difficult to construct any other $I^\pi=19/2^-$ state at such a low excitation. An $(\alpha, 4n)$ study [33] of the $N=86$ nucleus ^{150}Gd has identified a second 6^+ level as low as 2.12 MeV which may have a significant $3^- \times 3^-$ amplitude. Also here, an analogous 6^+ state has not been found [34, 35] in the isotone ^{152}Dy which was studied in similar (α, xn) experiments. In Fig. 6 we show the energy systematics of octupole excitations in Gd nuclei, and we have also included the possible candidates for two-phonon octupole excitations. Of course at present these identifications are quite speculative, in particular as long as no $(3^-)^2 \rightarrow 3^- B(E3)$ transition rate has been measured. Unfortunately the complex level schemes of the nuclei with 84 and more neutrons make the observation of such an $E3$ transition quite unlikely. However, due to the low energy of the octupole excitation, the Gd nuclei with $N > 82$ should be particularly favourable for the observation of the two-phonon octupole states.

5. Conclusion

The present study has established the ^{149}Gd high-spin energy spectrum up to ~ 4 MeV excitation, and

we have interpreted the results in terms of the spherical shell model.

The measured level energies of the three neutron $f_{7/2}^3$ multiplet are not well reproduced from the $\nu f_{7/2}^2$ energies of ^{148}Gd assuming pure two-nucleon interactions. The deviations suggest that long-range contributions become increasingly important already at $N=85$, only three neutrons above $N=82$. Nevertheless, the observed level spacings qualitatively resemble those calculated for a $\nu f_{7/2}^3$ multiplet.

Observation of the characteristic multiplets arising from $f_{7/2}$ valence neutrons has proven quite valuable for determining configuration assignments in ^{149}Gd as well as in other $N=85$ nuclei [26, 27, 32, 28]. Thus, collective excitations, or predominantly proton states, are associated with the $\nu f_{7/2}^3$ multiplet, whereas a $\nu f_{7/2}^2$ multiplet is found in combination with e.g. the $\nu h_{9/2}$ intrinsic excitation in the $N=85$ nuclei.

The $\nu f_{7/2}^3$ multiplet observed in combination with the $13/2^-$ state emphasizes the predominant octupole character of that state, and the analysis of highly positive parity levels suggests a ~ 2 MeV $\nu f_{7/2}$ to $\nu i_{13/2}$ single-particle energy separation.

Somewhat speculatively, a low-lying $19/2^-$ level which cannot be interpreted as valence nucleon state is assigned as a two-phonon octupole excitation. Although at present this assignment cannot be proven it fits in well with the properties of octupole excitations in the Gd region.

First results on the high spin structure of ^{149}Gd came from measurements in 1972 at the Berkeley 88" cyclotron, and we are indebted to M.R. Maier, R.M. Diamond, F.S. Stephens, and R.K. Sheline who participated in these early experiments. We thank M. Ogawa and R. Broda for their expert help during the measurements at Jülich, and we warmly acknowledge valuable and productive discussions with O. Schult. This work has been supported by a travel grant from the Nordic Committee for Accelerator-based Research.

References

1. Kleinheinz, P., Broda, R., Daly, P.J., Lunardi, S., Ogawa, M., Blomqvist, J.: Z. Phys. A - Atoms and Nuclei **290**, 279 (1979)
2. Broda, R., Behar, M., Kleinheinz, P., Daly, P.J., Blomqvist, J.: Z. Phys. A - Atoms and Nuclei **293**, 135 (1979)
3. Daly, P.J., Kleinheinz, P., Broda, R., Lunardi, S., Backe, H., Blomqvist, J.: Z. Phys. A - Atoms and Nuclei **298**, 173 (1980)
4. Kleinheinz, P.: Proc. Symp. on High Spin Phenomena in Nuclei, Argonne, (1979), ANL/PHY-79-4, p. 125
5. Bergström, I.: Proc. XVI Int. Winter Meeting on Nuclear Physics, Bormio, (1978), Iori, I. (ed.) Vol. II, p. 636
6. Lunardi, S., Ogawa, M., Maier, M.R., Kleinheinz, P.: Proc. Symp. on High Spin Phenomena in Nuclei, Argonne, (1979), ANL/PHY-79-4, p. 393, and Inst. f. Kernphysik, KFA-Jülich, Annual Report 1979, p. 51
7. Kleinheinz, P., Stefanini, A.M., Maier, M.R., Sheline, R.K., Diamond, R.M., Stephens, F.S.: Nucl. Phys. A **283**, 189 (1977)

8. Toth, K.S., Newman, E., Bingham, C.R., Rainis, A.E., Schmidt-Ott, W.-D.: *Phys. Rev. C* **11**, 1370 (1975)
9. Holland, G.E.: *Nucl. Data Sheets* **19**, 337 (1976)
10. Jackson, S.V., Starner, J.W., Daniels, W.R., Bunker, M.E., Meyer, R.A.: *Phys. Rev. C* **18**, 1840 (1978)
11. Kleinheinz, P., Sheline, R.K., Maier, M.R., Diamond, R.M., Stephens, F.S.: *Phys. Rev. Lett.* **32**, 68 (1974)
12. Rakel, D., Funk, E., Mihelich, J.: *Univ. of Notre Dame, Annual Report 1979*, p. 45
13. Piiparinen, M., Pengo, R., Nagai, Y., Kleinheinz, P., Roy, N., Carlén, L., Ryde, H., Lindblad, Th., Johnson, A., Hjorth, S.A., Hammarén, E.: *Proc. Int. Conf. on Nuclear Behaviour at High Angular Momentum, Strasbourg*, p. 63 (1980), and *BAPS* **24**, 827 (1979)
14. Piiparinen, M., Pengo, R., Nagai, Y., Kleinheinz, P., Roy, N., Carlén, L., Ryde, H., Lindblad, Th., Johnson, A., Hjorth, S.A.: *Inst. f. Kernphysik, KFA-Jülich, Annual Report 1979*, p. 53, and *Research Institute of Physics, Stockholm, Annual Report 1979*, p. 93
15. Moll, E., Kankeleit, R.: *Nukleonik* **7**, 80 (1965)
16. Ekström, C., Ingelman, S., Olsmats, M., Wannberg, B.: *Phys. Scr.* **6**, 181 (1972)
17. de-Shalit, A., Talmi, I.: *Nuclear Shell Theory*. New York: Academic Press 1963
18. Wapstra, A.H., Bos, K.: *At. Data Nucl. Data Tables* **19**, 177 (1977)
19. Blomqvist, J., Kleinheinz, P., Broda, R., Daly, P.J.: *Z. Phys.* (to be published)
20. Bergström, I., Blomqvist, J., Fant, B., Herrlander, C.J., Lindén, C.G., Wikström, K.: *Proc. XII Winter Meeting on Nuclear Physics, Villars, Switzerland, 1974*
21. Wilson, J., Faber, S.R., Daly, P.J., Ahmad, I., Borggreen, J., Chowdhury, P., Khoo, T.L., Lawson, R.D., Smither, R.K., Blomqvist, J.: *Z. Phys. A - Atoms and Nuclei* **296**, 185 (1980)
22. Toth, K.S., Bingham, C.R., Carter, H.K., Sousa, D.C., Zolnowski, D.R.: *BAPS* **23**, 627 (1978)
23. Harmatz, B., Ewbank, W.B.: *Nucl. Data Sheets* **25**, 113 (1978)
Rekstad, J.B., Løvholden, G., Lien, J.R., El-Kazzaz, S., El-legaard, C., Bjerregaard, J.H., Knudsen, P., Kleinheinz, P.: *Nucl. Phys. A* **348**, 93 (1980)
24. Hillis, D.L., Bingham, C.R., McClude, D.A., Kendrick, N.S., Jr., Hill, J.C., Raman, S., Ball, J.B., Harvey, J.A.: *Phys. Rev. C* **12**, 260 (1975)
Løvholden, G., Lien, J.R., El-Kazzaz, S., Rekstad, J., El-legaard, C., Bjerregaard, J.H., Knudsen, P., Kleinheinz, P.: *Nucl. Phys. A* **339**, 477 (1980)
25. Lessard, L., Gales, S., Foster, J.R., Jr.: *Phys. Rev. C* **6**, 517 (1972)
26. Piiparinen, M., Nagai, Y., Styczen, J., Kleinheinz, P.: *Proc. Int. Conf. on Nuclear Behaviour at High Angular Momentum, Strasbourg*, p. 53 (1980), and *Inst. f. Kernphysik, KFA-Jülich, Annual Report 1979*, p. 55
27. Piiparinen, M., Lunardi, S., Kleinheinz, P., Backe, H., Blomqvist, J.: *Z. Physik A - Atoms and Nuclei* **290**, 337 (1979)
28. Carlén, L., Jonsson, S., Lyttkens, J., Ryde, H., Strömberg, S., Hagemann, G.B., Herskind, B.: *Proc. Int. Conf. on Nuclear Interactions, Canberra, Springer, 1978*, p. 417, and *Dept. of Physics, Univ. of Lund, Annual Report 1979*, p. 17
Horn, D., Young, G.R., Lister, C.J., Baktash, C.: *Proc. Int. Conf. on Nuclear Behaviour at High Angular Momentum, Strasbourg*, p. 81 (1980), and *Phys. Rev. C* **23**, 1047 (1981)
29. Newman, E., Toth, K.S., Hensley, D.C., Schmidt-Ott, W.-D.: *Phys. Rev. C* **9**, 674 (1974)
30. Kleinheinz, P., Ogawa, M., Broda, R., Daly, P.J., Haenni, D., Beuscher, H., Kleinrahm, A.: *Z. Phys. A - Atoms and Nuclei* **286**, 27 (1978)
31. Lunardi, S., Ogawa, M., Backe, H., Piiparinen, M., Nagai, Y., Kleinheinz, P.: *Proc. Symp. on High Spin Phenomena in Nuclei, Argonne, (1979), ANL/PHY-79-4*, p. 403, and *Inst. f. Kernphysik, KFA-Jülich, Annual Report 1979*, p. 52
Lunardi, S.: *Proc. XVIII Winter School on Nuclear Structure, Bielsko-Biala (1980)*
32. Broda, R., Ogawa, M., Kleinheinz, P., Sheline, R.K., Richter, L.: *Proc. Symp. on High Spin Phenomena in Nuclei, Argonne, (1979), ANL/PHY-79-4*, p. 401, and *Inst. f. Kernphysik, KFA-Jülich, Annual Report 1978*, p. 29
33. Haenni, D.R., Sugihara, T.T.: *Phys. Rev. C* **16**, 120 (1977)
34. Jansen, J.F.W., de Voigt, M.J.A., Sujkowski, Z., Chmielewska, D.: *Nucl. Phys. A* **321**, 365 (1979)
35. Nagai, Y., Styczen, J., Piiparinen, M., Kleinheinz, P.: *Proc. Int. Conf. on Nuclear Physics, Berkeley*, p. 304 (1980)

M. Piiparinen
R. Pengo
Y. Nagai
E. Hammarén
P. Kleinheinz
Institut für Kernphysik
Kernforschungsanlage Jülich GmbH
Postfach 1913
D-5170 Jülich 1
Federal Republic of Germany

N. Roy
L. Carlén
H. Ryde
Department of Physics
University of Lund
S-22007 Lund 7
Sweden

Th. Lindblad
A. Johnson
S.A. Hjorth
J. Blomqvist
Research Institute of Physics
S-10405 Stockholm 50
Sweden

High-Spin Band Structure in ^{166}Yb

W. Waluś*, N. Roy, S. Jónsson, L. Carlén and H. Ryde

Department of Physics, University of Lund, Sölvegaten 14, S-223 62 Lund, Sweden

G. B. Hagemann, B. Herskind, J. D. Garrett and Y. S. Chen†

The Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark

and

J. Almberger‡ and G. Leander

Department of Mathematical Physics, Lund Institute of Technology, Sölvegaten 14A, S-223 62 Lund, Sweden

Received October 6, 1980; accepted November 20, 1980

Abstract

High-spin states in ^{166}Yb have been studied via the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction with 80 MeV ^{16}O ions from the NBI tandem accelerator. γ - γ coincidence data were accumulated with an array of four Ge(Li) and four NaI(Tl) detectors to favour high multiplicity events. Totally about 3×10^8 events were accumulated in the coincidence experiment. Measurements of the angular distribution of the γ -radiation and the conversion coefficients were furthermore performed. Four weakly populated side bands are observed besides the yrast cascade which is followed up to its 24^+ member. The ground state band has thus been identified to its 18^+ state, while the crossing Stockholm band becomes the yrast band from its 16^+ member. The S-band is established from its 12^+ state. The observed level energies and transition rates are well reproduced in calculations within the particle rotor model.

1. Introduction

In the mass region $A = 150$ – 170 the S-(Super or Stockholm) band [1] built upon aligned $(\nu_{13/2})^2$ orbits, usually crosses the ground state band (g.s.b.) around spin 14 and may cause back-bending, depending upon the interaction between the g.s. and S-band. The interpretation of the band structure and band crossings in rotational nuclei along the lines of Bohr and Mottelson [1] provides us with a means to compare experimental results with a microscopic theory and to extract quantities like the crossing frequency and the aligned angular momentum from the experimental data. The nucleus ^{166}Yb is of special interest, because *a priori* it would seem to be one of the best rotors which can be significantly populated at very high spins by (HI, xn) reactions. The identification of discrete lines in this work extends the information about the non-yrast bands from lighter and less rotational-like nuclei, and furthermore complements the gamma correlation work described elsewhere in these proceedings [2].

2. Experimental technique and results

States in ^{166}Yb were populated following the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction at a beam energy of 80 MeV, the beams being provided by the NBI tandem accelerator. The experiments con-

sisted of γ -ray angular distribution, γ - γ coincidence and conversion electron coefficient measurements. The reaction yields at this bombarding energy, with an isotopically enriched, metallic target of ^{154}Sm sputtered to a thickness of 1.5 mg cm^{-2} onto a lead backing, were about 77% ^{166}Yb , 15% ^{165}Yb and 7% ^{167}Yb .

2.1. Singles γ -ray measurements

With the target at an angle of 45° relative to the beam direction two sets of singles γ -ray spectra were obtained at 5 different angles, one with a Ge(Li) detector at angles ranging between 58° and 148° and the other with a Ge(Li) detector in a Compton-suppression set-up at angles between 0° and 90° . One stationary Ge(Li) detector placed below the target served as the monitor. In spite of the low counting rate, the data for the weak transitions obtained with the anti-Compton set-up proved to be superior to those with the other detector due to the reduced background. Efficiency calibrations at various angles were performed with a radioactive ^{152}Eu source placed at the target position. A typical spectrum obtained with the anti-Compton set-up at 90° is shown in Fig. 1. Two sets of angular distribution coefficients were obtained, one for each detector, by fitting the peak intensities to the expression $W(\theta) = A_0 + A_2 P_2(\cos \theta) + A_4 P_4(\cos \theta)$, after normalizing them to the monitor yields and correcting for the dead times of the ADC's and the variations of the relative efficiency at different angles. The results from the two detector set-ups are consistent. The results of the angular distribution measurements are summarised in Table I. The energy calibration was done by recording a singles γ -ray spectrum at 90° along with the spectrum from a ^{152}Eu source placed near the target.

2.2. γ - γ coincidence measurements

γ - γ coincidence measurements were performed with an array of four Ge(Li) detectors and four NaI(Tl) detectors. The gains of the amplifier of the Ge(Li) detectors were matched to be equal. Only those coincidence events were accumulated on magnetic tape for off-line analysis, for which two Ge(Li) counters in addition to at least one of the remaining Ge(Li) detectors or one of the NaI(Tl) detectors were triggered. In all, about 300 million pairs of events were accumulated. The tapes were sorted for all the possible combinations of pairs of detectors and the resulting spectra, after background subtrac-

* On leave of absence from the Jagellonian University, Cracow, Poland.

† On leave of absence from the Institute of Atomic Energy, Peking, China.

‡ Research Institute of Physics, Stockholm, Sweden.

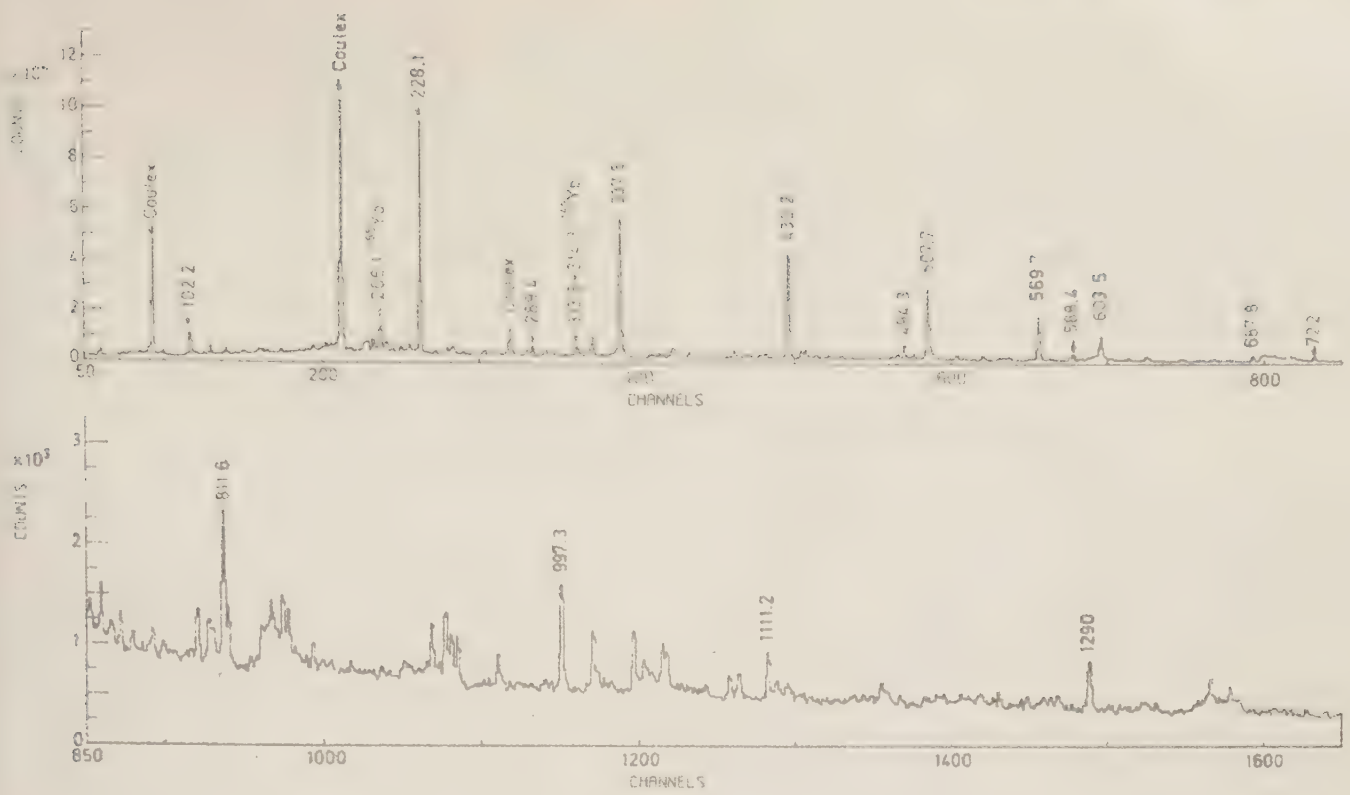


Fig. 1. Singles γ -ray spectrum at 90° to the beam direction, using an anti-Compton set-up, taken during bombardment of a ^{154}Sm target with 80 MeV ^{16}O .

Table I. The energies, intensities and angular distribution coefficients for the transitions assigned to ^{166}Yb following the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction at 80 MeV

E_γ^a (keV)	Intensity ^b	Ang. dist. coeff. ^c		$I_1^{\pi d} \rightarrow I_1^{\pi d}$
		A_2/A_0	A_4/A_0	
102.2		0.27(03)	-0.06(03)	$2^+ \rightarrow 0^+$
114				$8^- \rightarrow 7^-$
152				$10^- \rightarrow 9^-$
206 ^e	16	0.21(07)	-0.05(08)	$8^- \rightarrow 6^-$
228.1	987	0.30(03)	-0.09(03)	$4^+ \rightarrow 2^+$
248 ^e	8			$6^- \rightarrow (4^-)$
274 ^e	Weak			$(7^-) \rightarrow (7^-)$
276 ^e	Weak			$(7^-) \rightarrow (6^-)$
289 ^e				$(4^-) \rightarrow 5^+$
289.4	55	0.30(02)	-0.10(02)	$10^- \rightarrow 8^-$
301.4	14	0.42(05)	0.02(05)	$(8^-) \rightarrow (6^-)$
337.5	1000	0.32(03)	-0.11(03)	$6^+ \rightarrow 4^+$
341	Weak			$(10^-) \rightarrow 9^+$
354.4	28	0.28(03)	-0.03(04)	$(10^-) \rightarrow (8^-)$
356 ^e	16			$12^+ \rightarrow 12^+$
366 ^e	5	0.29(02)	-0.15(02)	$14^+ \rightarrow 12^+$
367.6 ^e	65			$12^- \rightarrow 10^-$
368 ^e				$(7^-) \rightarrow 6^-$
375.8	37	0.27(02)	-0.12(03)	$16^+ \rightarrow 14^+$
400.4	51	0.34(03)	-0.10(03)	$(12^-) \rightarrow (10^-)$
403 ^e	17			$17^- \rightarrow 16^+$
430.2	856	0.31(03)	-0.13(03)	$8^+ \rightarrow 6^+$
432 ^e	Weak			$(8^-) \rightarrow 7^+$
437.6	63	0.27(03)	-0.08(03)	$14^- \rightarrow 12^-$
445.8 ^e	33	0.14(09)	-0.02(07)	$13^- \rightarrow 11^-$
446 ^e				$9^+ \rightarrow 7^+$
459.4	27	0.36(05)	-0.19(05)	$(14^-) \rightarrow (12^-)$
490.8	43	0.32(06)	-0.07(09)	$15^- \rightarrow 13^-$
494.3	128	0.35(010)	-0.09(01)	$16^+ \rightarrow 14^+$
496.7	22	0.38(04)	-0.18(05)	$(11^-) \rightarrow 9^+$

Table I. (continued)

E_γ^a (keV)	Intensity ^b	Ang. dist. coeff. ^c		$I_1^{\pi d} \rightarrow I_1^{\pi d}$
		A_2/A_0	A_4/A_0	
499.5	45	0.33(03)	-0.13(03)	$16^- \rightarrow 14^-$
507.7	645	0.32(08)	-0.09(01)	$10^+ \rightarrow 8^+$
508 ^e				$(6^-) \rightarrow 5^+$
509 ^e	160	0.23(03)	-0.11(03)	$18^+ \rightarrow 16^+$
527.5	14	0.26(07)	-0.01(11)	$(16^-) \rightarrow (14^-)$
538 ^e	19	-0.26(24)	-0.16(25)	$6^- \rightarrow 5^+$
538.2 ^e	35	0.47(13)	0.04(14)	$17^- \rightarrow 15^-$
550 ^e	15	0.22(04)	0.03(07)	$13^+ \rightarrow 11^+$
552.8	32	0.20(05)	-0.03(08)	$18^- \rightarrow 16^-$
569.7	480	0.33(03)	-0.11(03)	$12^+ \rightarrow 10^+$
575.1	17	-0.30(18)	0.15(17)	$15^- \rightarrow 14^+$
586.2 ^e	30	0.22(07)	0.34(09)	$19^- \rightarrow 17^-$
588.4	69	0.36(05)	-0.02(08)	$20^+ \rightarrow 18^+$
592 ^e	14	0.27(17)	-0.07(22)	$16^+ \rightarrow 14^+$
592 ^e	10			$(18^-) \rightarrow (16^-)$
600.1	25	0.25(12)	0.05(13)	$20^- \rightarrow 18^-$
603.5	250	0.31(02)	-0.13(02)	$14^+ \rightarrow 12^+$
629 ^e	24	0.29(03)	-0.05(07)	$(6^+) \rightarrow 5^+$
630 ^e				$21^- \rightarrow 19^-$
649 ^e	10			$22^- \rightarrow 20^-$
649 ^e	Weak			$(20^-) \rightarrow (18^-)$
660 ^e	7			$5^+ \rightarrow 6^+$
667	25	Doppler broadened		$22^+ \rightarrow 20^+$
674 ^e	13	0.13(09)	-0.33(09)	$23^- \rightarrow 21^-$
687.8	45	-0.21(02)	0.10(03)	$13^- \rightarrow 12^+$
701				$18^+ \rightarrow 16^+$
709 ^f	4			$3^+ \rightarrow 4^+$
710.3	39	0.34(03)	-0.02(05)	$16^+ \rightarrow 14^+$
722.0	69	0.35(01)	-0.05(02)	$14^+ \rightarrow 12^+$
739		Doppler broadened		$24^+ \rightarrow 22^+$

Table I. (continued)

E_γ^a (keV)	Intensity ^b	Ang. dist. coeff. ^c		$I_1^{\pi d} \rightarrow I_2^{\pi d}$
		A_2/A_0	A_4/A_0	
811.6	39	-0.15(07)	0.01(06)	$11^- \rightarrow 10^+$
830 ^f	22			$2^+ \rightarrow 2^+$
860	10			$(7^-) \rightarrow 8^+$
925.6	15	0.27(05)	-0.16(07)	$12^{+?} \rightarrow 10^+$
932 ^f	21			$2^+ \rightarrow 0^+$
936 ^f	16			$3^+ \rightarrow 2^+$
997.3	38	-0.19(03)	0.15(07)	$5^+ \rightarrow 4^+$
1037	22	-0.31(06)	0.05(07)	$7^+ \rightarrow 6^+$
1053	16	-0.31(07)	0.03(08)	$9^+ \rightarrow 8^+$
1111.2	19	-0.22(04)	0.04(05)	$9^- \rightarrow 8^+$
1122	8			$(5^-) \rightarrow 6^+$
1290	25	-0.19(04)	0.06(04)	$(7^-) \rightarrow 6^+$
1460 ^e				$(5^-) \rightarrow 2^+$

^a Energy uncertainties are 0.2 keV for strong transitions (rel. int. > 50), rising to 0.5 keV for weaker transitions.

^b Intensities are given relative to the $6^+ \rightarrow 4^+$ g.s.b. transition.

^c Only fitting errors are given.

^d Assignments in brackets are tentative.

^e Weak or doublet. Intensities wherever given for individual transitions, are based on the coincidence data, uncorrected for the angular correlation effects.

^f Lines known from the decay of ^{166}Lu . Assignments are based on the observed branching ratios.

tion, were added together. Examples of coincidence spectra are shown in Fig. 2. In a similar coincidence run for studying the ^{167}Yb nucleus with an 80 MeV ^{17}O beam, the yield of ^{166}Yb was about 50% with no observable yield found for ^{165}Yb . As many transitions in ^{165}Yb have the same or nearly the same energy as those in ^{166}Yb , the data from the latter experiment helped to remove ambiguities concerning many weak transitions and to confirm the level scheme of ^{166}Yb .

2.3. Conversion coefficient measurements

In order to ascertain the multiplicities of the transitions, the conversion electron spectrum was obtained at 55° with a solenoid transporter and a cooled Si(Li) detector. The electron intensities were recorded in the range from about 600 keV to about 1200 keV as this region contained most of the interband transitions. A γ -ray spectrum was also recorded simultaneously at -55° . The conversion coefficients were normalized to the $\alpha_K(E2)$ values of the 603, 710 and 722 keV transitions. The results of the conversion coefficient measurements have led to the assignment of negative parity of two side bands.

3. Construction of the level scheme

The yrast sequence of levels in ^{166}Yb was earlier known up to spin 20^+ . Many low-lying levels up to an excitation energy of 2.43 MeV are known from the radioactive decay studies [3] of ^{166}Lu . The level scheme of ^{166}Yb , as deduced from the present work, is presented in Fig. 3. Previously known levels, not seen in this work, are not included in the figure. The spin and parity assignments are based on the angular distribution and conversion coefficient measurements with frequent reference to previous measurements. All the transitions within a band are found to be of stretched E2 character. The ordering of the transitions within a band is based on their coincidence relationships and their relative intensities.

3.1. The ground state and S-bands

The yrast sequence of levels has been extended up to a spin of 24^+ and the g.s.b. to a spin of 18^+ . Although the 667 and 739 keV lines, depopulating the 22^+ and the 24^+ levels, respectively, show considerable Doppler broadening, their angular anisotropies are well enough determined and have the same magnitude as expected for stretched E2 transitions high up in a

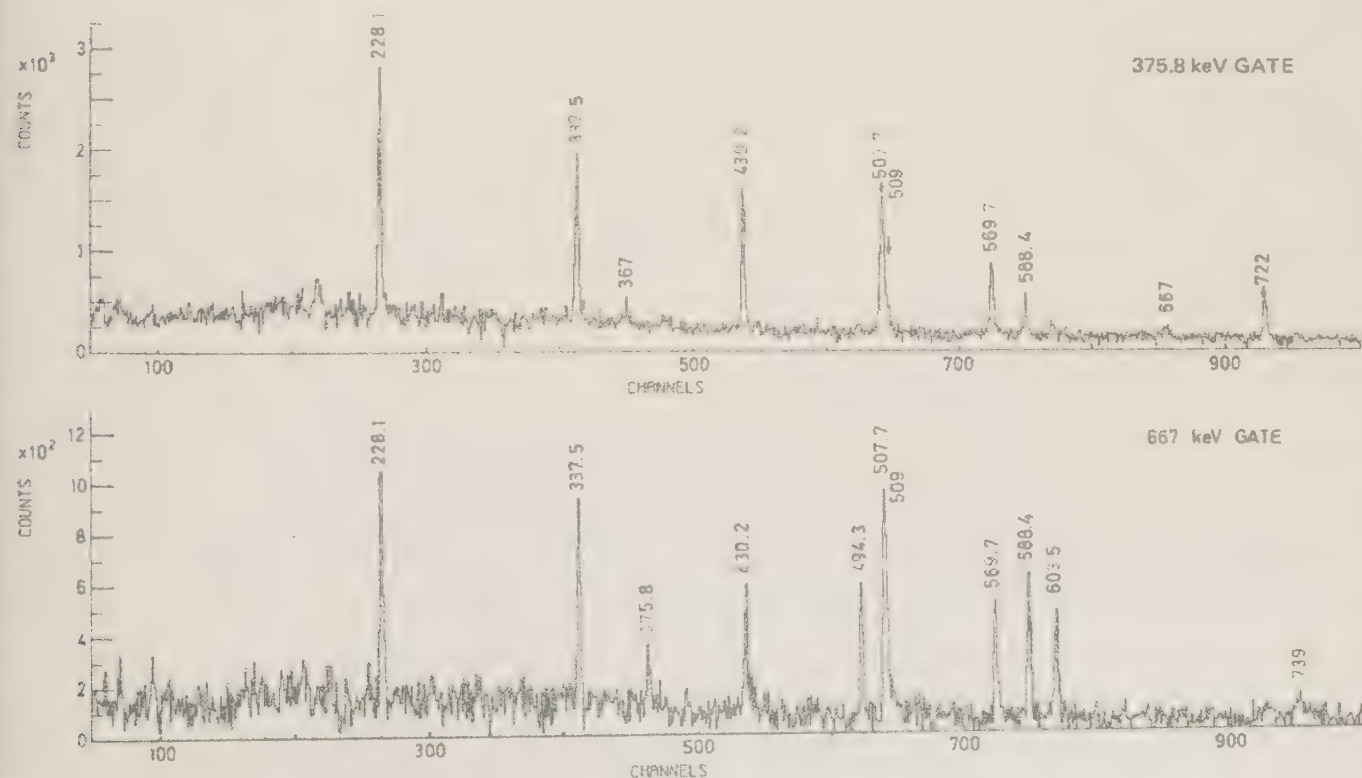


Fig. 2. Ge(Li) γ - γ coincidence spectra (background - subtracted) observed following the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction at 80 MeV.

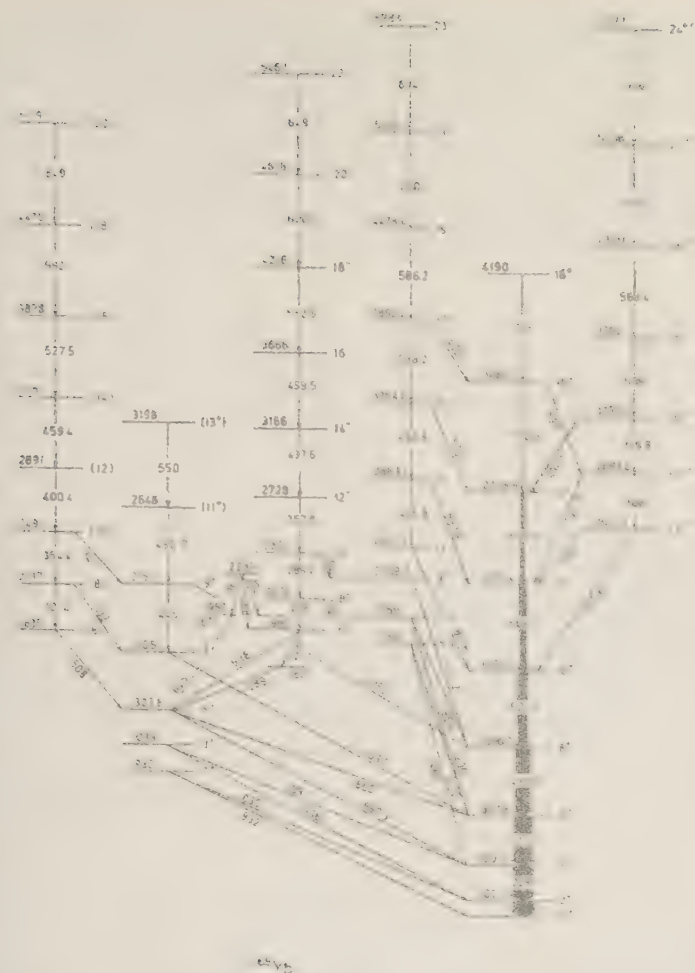


Fig. 3. Level scheme of ^{166}Yb showing states populated by the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction.

cascade, and thereby justify their assignments. The 356 keV transition from the 12^{+} to the 12^{+} state could only be inferred from the coincidence data. Its intensity, the angular distribution coefficients and hence the M1/E2 mixing ratio could not be determined due to the presence of a contaminant line from the radioactive decay of the reaction products. The intensity of the 592 keV 16^{+} to 14^{+} state transition could only be inferred from the coincidence data due to the presence of another transition having nearly the same energy.

3.2. The odd-spin negative parity band

One band with odd-spin and negative parity has been identified. The 11^{-} member of this band and the higher lying members are joined by a cascade of stretched quadrupole transitions and connected to the g.s.b. by four interband transitions. The measured K -conversion coefficient of the 688 keV transition confirms the negative parity assignment of this band. The intensity ratios of the intraband transitions to the interband transitions to the g.s.b. decrease going down the band. The intraband transitions among the 5^{-} , 7^{-} , 9^{-} and the 11^{-} states at 1790, 1959, 2209 and 2417 keV are too weak to be detected in the coincidence work. The 5^{-} and 7^{-} states are known from the work of de Boer et al. [3]. The stretched E1 character of the transition from the 9^{-} state to the 8^{+} member of the g.s.b. is established from angular distribution and conversion coefficient measurements.

3.3. The even-spin negative parity band

The level at 1865 keV, which lies at the bottom of the even-spin negative parity band, has been observed in the radioactive decay of ^{166}Lu [3] and assigned a spin and parity of 6^{-} . The regularity and the stretched E2 character of the cascade transitions populating this level justify the classification of this cascade as a band. Furthermore, the state 10^{-} at 2361 keV decays by an intense, mixed transition to the level at 2209 keV, which is assigned as having spin and parity 9^{-} in this study. This mixed transition is assumed to be of the M1/E2 type. Multipole admixture of higher order than quadrupole would require the level at 2361 keV to be an isomer with a lifetime of the order of microseconds.

3.4. The γ -vibrational band

Several members of the γ -vibrational band have been observed earlier in the radioactive decay of ^{166}Lu [3]. The 5^{+} member of this band is populated rather strongly in the present study and angular distribution and the conversion electron data confirm the 5^{+} assignment. The 2^{+}_{γ} and 3^{+}_{γ} levels are populated very weakly and we infer their presence in this study from the observed branching ratios of the decays of these levels. The 7^{+} level at 1705 keV has been found to decay by a stretched M1 transition to the 6^{+} state of the g.s.b. It is to be noted that this level is not the same as the 7^{+} level found earlier [3]. The assignment of the higher lying members of this band is only tentative and is based upon the observed decay properties of these levels, the systematic variation of the level differences and the similarity to the $N = 96$ isotone ^{164}Er .

3.5. An unassigned rotational band and further levels

A band of levels of unknown spins and parity and built on the 1835 keV state is observed in the present study. This band is connected by means of three weak interband transitions to the proposed γ -vibrational band, and the energies of these transitions are too close to strong g.s.b. transitions to make a determination of their multipole character possible in the present experiment. The tentatively suggested spins and negative parity are based on the observation of a similar band in ^{164}Er starting in that case with spin (8) at an excitation energy of 2091 keV.

The levels at 1617, 1957 and 2233 keV (cf. Fig. 3) are known from the work of de Boer et al. [3]. Our identification of these levels is based solely on the observation of some transitions originating from these levels in our coincidence spectra. Only these transitions are shown in Fig. 3 and other decay modes of these levels, not established in the present study, are excluded from the figure.

4. Theoretical considerations

A crossing of two bands is sometimes referred to as virtual or real, depending on whether or not an interaction between the two bands is likely to deflect a gamma cascade from one band to another. The real crossing known in the deformed rare-earth nuclei all occur between bands which do not interact because of different signature or parity. The crossings between the g.s. and S -bands, on the other hand, are generally virtual and an yrast cascade tends to stay yrast. However, it is illustrated by the case of ^{166}Yb that even when the interaction between the bands is not forbidden, there may be situations when the nucleus prefers to follow a band of given structure rather than

the trajectory of lowest energy, In Section 4.1 the general conditions for such behaviour are formulated in terms of the band parameters. In Section 4.2 it is pointed out that the different cascade patterns in the two $N=96$ isotones ^{164}Er and ^{166}Yb arise naturally in particle-rotor calculations based on the notion of $(\nu i_{13/2})^2$ bands crossing the ground band. Section 4.3 contains a phenomenological analysis in terms of cranking model quantities for the positive and negative parity bands shown in Fig. 3.

4.1. Two-band analysis

A schematic model can be used to derive the conditions when a crossing between two weakly interacting bands is mainly virtual or mainly real. The energies of the two unperturbed bands as functions of the spin I are written

$$E = A_i(I - J_i)^2 + E_i^0, \quad i = 1, 2$$

They cross at a spin I_c . The difference $J_2 - J_1$ between the aligned spins is denoted j . Perturbed bands are obtained by diagonalizing a two by two matrix with an off-diagonal matrix element V . It is then straightforward to find the perturbed energies and the relative transition rates. The branching ratio of the transition rates from the lowest state of spin I to the upper and lower states of spin $(I-2)$ are, in two special cases

$$\frac{T(I_c \rightarrow I_c - 2)}{T(I_c \rightarrow (I_c - 2)')} = \left[\frac{1}{1 - (j/I_c)} \right]^5 + O(V)$$

and

$$\frac{T(I_c + 1 \rightarrow I_c - 1)}{T(I_c + 1 \rightarrow (I_c - 1)')} = \frac{V}{A_j} \left[\frac{1 - \frac{1}{2}(j/I_c)}{1 - (j/I_c)} \right]^5 + O(V^2)$$

respectively. In the first case the bands cross at one of the discrete spins where states exist, and it is seen that the yrast cascade tends to remain yrast. In the second case, where the bands cross in between the discrete states, the yrast cascade tends to leave the yrast line if V is sufficiently small. For given A and j this situation is clearly favoured by a large spin I_c .

A two-band analysis along the lines of [4] for the energy levels of ^{164}Er and ^{166}Yb is described in Section 4.3 below. It gives $I_c \sim 16$ in the former nucleus and $I_c \sim 15$ in the latter which thus accounts for the observed difference in the gamma cascade of the two nuclei. Other parameters obtained from the two-band analysis are the interaction V between the two unperturbed bands, and the inertia parameters. The branching ratios of the decays of the g.s. and the S -band suggest an interaction V of the order of 45–50 keV.

4.2. Particle-rotor analysis

It has recently been shown [5, 6] that the many-BCS-quasiparticle plus rotor Hamiltonian within a $(i_{13/2})^2$ valence space can be adjusted to give an accurate description of the energies along the g.s. and S -bands of ^{164}Er and ^{166}Yb . If the energies are correct it is expected that the calculation also accounts for branching ratios, and in particular the observed differences between the two nuclei in this respect. For ^{166}Yb the adjustable parameters [5] ($\theta_0 = 35.463 \text{ MeV}^{-1}$, $C = 0.0039308 \text{ MeV}^3$, $\lambda = 0.0545 \text{ MeV}$ above $\epsilon_{5/2}$ and $\Delta = 0.669952 \text{ MeV}$) were fitted in [5] to the yrast levels of spin $I = 0-20$, so the energies of all non-yrast levels, and, furthermore, the branching ratios, can be regarded as predictions of the model. A calculated branching of the yrast cascade at $I = 16$ has been reported earlier [7].

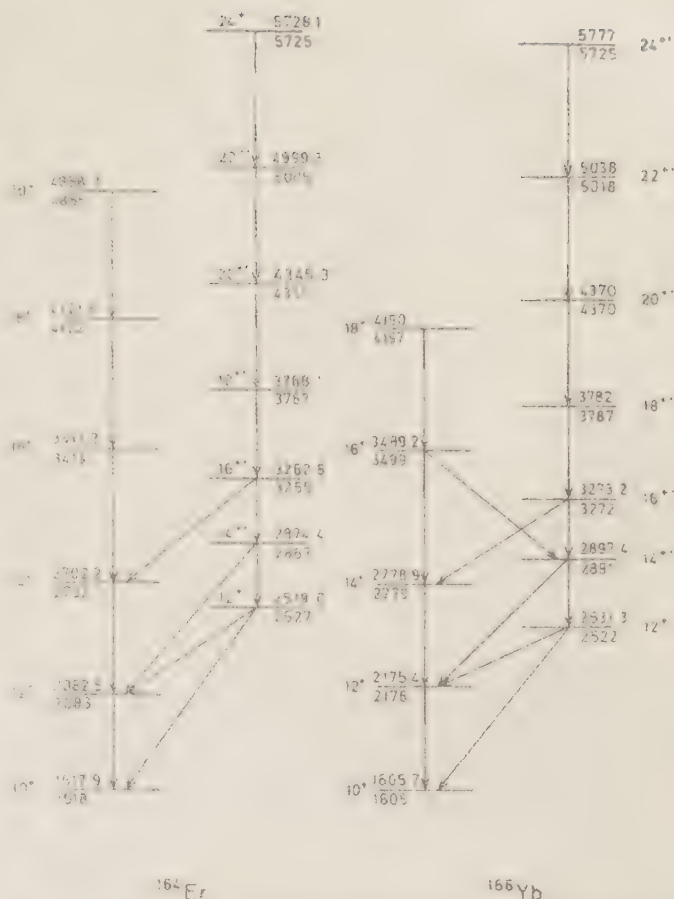


Fig. 4. Comparison of the theoretical and experimental level energies for the g.s. and S -bands of ^{164}Er and ^{166}Yb . The calculated energies are shown below the experimental values.

A comparison between results of the model calculations and experiments is given for the two nuclei in Fig. 4 and Table II. The energies of the non-yrast levels in ^{166}Yb are of course not quite as well reproduced as in ^{164}Er , where levels from the high-spin continuation of the g.s.-band and the low-spin continuation of the S -band were included in the parameter fitting procedure. Nevertheless, the calculation is sufficiently accurate to describe the branching of the electromagnetic decay, cf. Table III. The transitions following the unperturbed bands through the crossing are indeed significantly stronger for ^{166}Yb than for ^{164}Er . Thus the transition from 16^+ to 14^+ has been seen in the ^{166}Yb case but not in ^{164}Er . A decay branch from the 12^+ level to the 12^+ level as well as to the 10^+ level is measured in ^{166}Yb . The 12^+ to 12^+ transition is of particular interest because, according to the calculation, it is an almost pure M1 from the S -band to the g.s.-band. The parameters employed here for calculating the electromagnetic transition rates are $Q = 7b$, $e^{\text{eff}} = e$, $g_s^{\text{eff}} = 0.6g_s^{\text{free}}$, $g_l = 0$ and $g_R = Z/A$. A complication which should be noted is that the observed 12^+ level comes 9 keV above the calculated one, and just as in ^{164}Er , this may indicate an admixture of the 12^+ level from the gamma band [8].

4.3. Cranking model analysis

The alignment plots [9] for the various bands are shown in Fig. 5. The g.s. and the other bands except the S -band, are fitted with the parameters [9] $J_0 = 29 \text{ MeV}^{-1}\hbar^2$ and $J_1 = 136 \text{ MeV}^{-3}\hbar^4$. The corresponding parameters for the S -band have been adjusted to give a constant value of i_x above the backbend

Table II. Comparison of the theoretical and experimental level energies for the g.s. and S-bands of ^{164}Er and ^{166}Yb . The calculated energies are shown in brackets alongside the experimental values.

^{164}Er			^{166}Yb		
g.s.b.		S-band	g.s.b.		S-band
0 ⁺	0 (0)		0 (0)		
2 ⁺	91.3 (91.5)		102.2 (101.9)		
4 ⁺	299.4 (299.9)		330.3 (330.1)		
6 ⁺	614.3 (615.1)		667.8 (667.8)		
8 ⁺	1024.5 (1025.0)		1098.0 (1097.8)		
10 ⁺	1517.9 (1518.0)		1605.7 (1605.3)		
12 ⁺	2082.5 (2082.7)	2519.0 (2527.3)	2175.4 (2176.4)		2531.3 (2522.1)
14 ⁺	2702.2 (2702.4)	2874.4 (2866.6)	2778.9 (2779.3)		2897.4 (2890.5)
16 ⁺	3411.2 (3413.0)	3262.6 (3255.0)	3489.2 (3499.1)		3273.2 (3271.9)
18 ⁺	4121.5 (4122.2)	3768.1 (3767.1)	4190 (4196.6)		3782 (3786.6)
20 ⁺	4868.2 (4865.5)	4345.3 (4350.7)			4370 (4370.0)
22 ⁺		4999.3 (5005.0)			5038 (5018.0)
24 ⁺		5728.1 (5724.9)			5777 (5725.0)

and are $J_0 = 33.5 \text{ MeV}^{-1} \hbar^2$ and $J_1 = 62.5 \text{ MeV}^{-3} \hbar^4$. The fact that the same values of the moment of inertia parameters generally do not give constant alignment values both below and above the backbend has been discussed by Bengtsson [10] and is probably due to the changes in the core associated with the backbending effect. The g.s. and S-bands show up with nearly constant alignments after correction for their mutual interaction, which is assumed to be constant and equal to 50 keV. The point corresponding to the $18^+ \rightarrow 16^+$ g.s.b. transition shows unbending, which is due to a crossing with the S'-band in the particle-rotor calculation.

The experimental Routhians are shown in Fig. 6. The S-band Routhian crosses that of the g.s.b. at $\hbar\omega = 0.28 \text{ MeV}$. The odd-spin odd parity band shows regular behaviour only above spin 11⁺. This band and the even-spin negative parity band built on the 6⁻ state at 1865 keV could be the two lowest bands with $\alpha = 1$ and 0 respectively, built on the neutron levels labelled $[642\frac{1}{2}]$ and $[523\frac{1}{2}]$ at zero frequency [9].

The extrapolated experimental Routhians for these bands cross the g.s. band at $\hbar\omega \approx 0.36 \text{ MeV}$. No concrete assignments have been made for the band with the band head at 1835 keV. The spin of the band head is probably 6. If this is the case, then this band could be the other $\alpha = 0$ even-spin negative parity

band based on the same neutron quasiparticle configuration as mentioned above. It may be noted, however, that the lowest identified member of a similar band in $N = 96$ isotone ^{164}Er has been assigned a spin (8) and has been suggested [9] to belong to the neutron configuration $[642\frac{1}{2}][505\frac{1}{2}] K = 8$.

5. Conclusions

Judging by the first few states of the g.s. bands, the nucleus $^{166}\text{Yb}_{96}$ is more appropriately classified as a stable deformed rotational nucleus than the more neutron-deficient rare-earth isotopes. Previously the only high-spin levels known were the yrast levels up to spin 20 [11]. In the present work six bands are identified, up to spin 24 on the yrast line and up to 23 in one of the side bands, thereby extending the systematics of high-spin band structure into the region of well-deformed nuclei. Many of the states were also populated and assigned similar spins and parities in a parallel study of the $^{162}\text{Dy}(^9\text{Be}, 5n)^{166}\text{Yb}$ reaction at Brookhaven [12]. The positive-parity bands are presumably aligned neutron $(i_{13/2})^2$ configurations and the negative-parity

Table III. Comparison of the theoretical and experimental $B(E2)$ and $B(M1)$ ratios for g.s. and S-bands of ^{164}Er and ^{166}Yb

	^{166}Yb		^{164}Er	
	th.	exp.	th.	exp.
$B(E2, 16^+ \rightarrow 14^+)$	1:1.3	1:0.9	1:0.6	—
$B(E2, 16^+ \rightarrow 14^+)$				
$B(E2, 16^+ \rightarrow 14^+)$	1:1.2	1:0.9	1:0.5	1:0.4
$B(E2, 16^+ \rightarrow 14^+)$				
$B(E2, 14^+ \rightarrow 12^+)$	5.2:1	—	35:1	—
$B(E2, 14^+ \rightarrow 12^+)$				
$B(E2, 14^+ \rightarrow 12^+)$	4.4:1	2.1:1	24:1	22:1
$B(E2, 14^+ \rightarrow 12^+)$				
$B(M1, 12^+ \rightarrow 12^+)$	2000:1	1600:1	1200:1	1250:1
$B(E2, 12^+ \rightarrow 10^+)$				

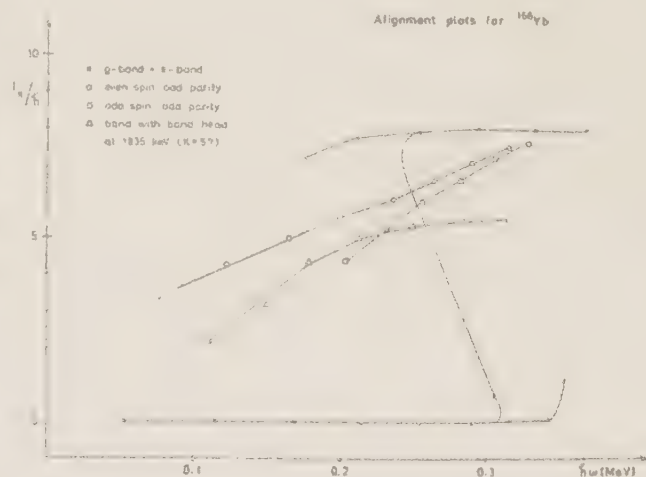


Fig. 5. Plot of the alignment vs. rotational frequency for the various bands in ^{166}Yb . The g.s. and the other bands except the S-band are fitted with the parameters [9] $J_0 = 29 \text{ MeV}^{-1} \hbar^2$ and $J_1 = 136 \text{ MeV}^{-3} \hbar^4$. The corresponding parameters for the S-band have been adjusted to give a constant value of i_x above the backbending and are $J_0 = 33.5 \text{ MeV}^{-1} \hbar^2$ and $J_1 = 62.5 \text{ MeV}^{-3} \hbar^4$.

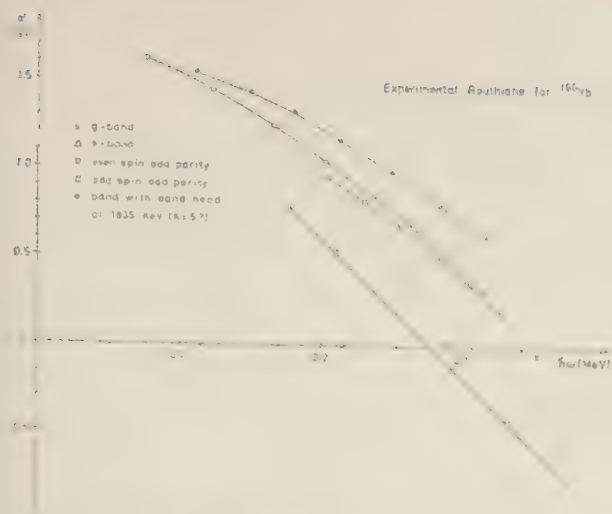


Fig. 6. Experimental Routhians for the various bands in ^{166}Yb .

bands could be neutron $(i_{13/2})(h_{11/2})$ configurations [9]. The VMI parameters, Routhians and values for the aligned angular momentum are extracted from the data. A gamma correlation experiment [13] has also been made recently, which reaches the very high-spin states in the isotopes around ^{166}Yb , and the information obtained in the present work about the detailed spectroscopy up to spins above 20 should be a valuable aid in the interpretation of the results [2, 14].

The crossing between the g.s. and S-bands of ^{166}Yb has a special feature. It is the first known case of a crossing between two interacting bands in deformed rare-earth nuclei where a significant fraction of the cascade intensity leaves the trajectory of the lowest energy in order to follow an unperturbed band characterized by intrinsic structure. The mechanism is a small interaction combined with a band crossing spin in between the even integer values where there are physical states. Heating of the nucleus by this mechanism may occur more frequently for

band crossings at higher spins. A number of interband transitions are observed in the present case at and just below the crossing, which provide more of a test for theory than the data on other backbending rare-earth nuclei. The levels and the M1 and E2 transitions matrix elements obtained from an $(i_{13/2})^2$ plus rotor calculation, made before the experiment and fitted to the energies along the yrast line, turn out to be consistent in detail with the observed energies and intensities.

Acknowledgements

We wish to express our sincere thanks to the Nordic Committee for Acceleratorbased Research for financial support.

References

1. Bohr, A. and Mottelson, B. R., Proc. Int. Conf. on Nuclear Structure, Tokyo (1977).
2. Delaplanque, M. A., Physica Scripta 23, 000 (1981).
3. de Boer, F. W. N., Goudsmit, P. F. A., Koldewijn, P. and Meyer, B. J., Nuclear Physics A225, 317 (1974).
4. Bengtsson, R. and Frauendorf, S., Nuclear Physics A314, 28 (1979).
5. Almberger, J., Hamamoto, J. and Leander, G., Nuclear Physics A333, 184 (1980).
6. Almberger, J., Hamamoto, J. and Leander, G., Physica Scripta (in press).
7. Chen, Y. S., Garrett, J. D., Almberger, J. and Leander, G., Physics Letters 94B, 468 (1980).
8. Johnson, N. R., Cline, D., Yates, S. W., Stephens, F. S., Riedinger, L. L. and Ronningen, R. H., Phys. Rev. Lett. 40, 151 (1978).
9. Bengtsson, R. and Frauendorf, S., Nuclear Physics A327, 139 (1979).
10. Bengtsson, R., To be published in J. de Phys.
11. Lederer, C. M. and Shirley, V. S., Table of Isotopes, 7th edition, John Wiley & Sons, New York (1978).
12. Sunyar, A. W., Private communication.
13. Herskind, B., Private communication.
14. Leander, G., Chen, Y. S. and Milsson, B. S., Physica Scripta 23, 000 (1981).

Near Yrast Spectroscopy of $^{165-167}\text{Yb}$

N. Roy, S. Jönsson, H. Ryde and W. Waluś^{*}
Department of Physics, University of Lund,
S-223 62 LUND, Sweden

and

J.J. Gaardhøje, J.D. Garrett, G.B. Hagemann and B. Herskind
The Niels Bohr Institute, University of Copenhagen.
DK-2100 Copenhagen, Denmark.

* On leave of absence from Jagellonian University, Cracow,
Poland.

ABSTRACT: The lowest $(\pi, \alpha) = (+, +), (+, -)$ and $(-, +)$ rotational sequences in $^{165,167}\text{Yb}$ as well as the lowest $(-, -)$ sequence in ^{165}Yb have been established to high spins. The single-quasineutron portions of these sequences are used to construct two- and three-quasineutron states which are compared to the corresponding configurations in $^{165,166,167}\text{Yb}$. Such a comparison indicates that the residual interactions between two quasineutrons are nearly independent of $\hbar\omega$ and configuration (for those studied), are attractive and are equal to about 300 keV. For three-quasineutron configurations an $\hbar\omega$ dependence is observed in the residual interaction, which can be interpreted as a reduction in alignment for the three-quasineutron configurations, a result of reduced pairing. Difficulties in reproducing the signature-dependent energy-splitting and band-crossing frequencies in the positive-parity decay sequence are not completely understood. The signature dependence of the interband-intraband branching ratios as well as of the interband M1/E2 mixing ratios provide an experimental justification of the signature dependence of $B(M1)$ transition rates recently suggested by Hamamoto.

NUCLEAR REACTIONS $^{152,154}\text{Sm}(^{17,18}\text{O}, xn)$, $x=4,5$, $E=80-84$ MeV; measured $\gamma\gamma$ -coin, $\gamma(\theta)$, α_K . $^{165,167}\text{Yb}$ deduced levels, J^π , $B(M1)$. CSM calculations. $^{165,167}\text{Yb}$ extracted one- and three-quasineutron Routhians and alignments. $^{165,166,167}\text{Yb}$ construction of two- and three-quasineutron Routhians from one-quasineutron Routhians. ^{166}Yb deduced residual interaction between two quasineutrons. Enriched targets, Ge(Li) detectors, NaI(Tl) array, Compton-suppressed Ge(Li), Compton-suppressed coincidence set-up, mini-orange spectrometer with Si(Li) detector.

1. Introduction

With the advent of higher-energy heavy-ion beams and improved γ -ray detection techniques it has become possible to not only extend the yrast sequence of nuclear states to higher angular momentum^{1,2)}, but also to establish additional rotational bands quite high in angular momentum^{3,4)}. Such detailed data for rotational bands based on several different intrinsic nuclear configurations have enticed theorists^{5,6)} to proceed with comprehensive detailed calculations of the spectrum of quasiparticle states in a rotating deformed nuclear potential. A selection of earlier references on such cranked Hartee-Fock-Boguljubov or cranked shell-model (CSM) calculations is contained in ref.⁷⁾. With the initial success (see e.g. refs.^{4-6,8-10)}) of interpreting the spectrum of energy levels in the decay scheme in terms of excitation energies of specific intrinsic configurations in a rotating frame, it seems important to establish the systematics of such quasineutron configurations as a function of neutron number.

The present article, which is a part of such a systematic study of near-yrast spectroscopy in the Yb nuclei^{4,8,11,12)}, reports new level-scheme information for ^{165}Yb and ^{167}Yb and discusses near-yrast spectroscopy in $^{165-167}\text{Yb}$. The paper draws heavily on the data for the ^{166}Yb level scheme which was reported recently^{11,13)}. A preliminary report of these data is contained in ref.¹⁴⁾, and some of the data were used in a recent report¹⁵⁾ of the systematics of band-crossing frequencies corresponding to the alignment of the first pair of $i_{13/2}$ quasineutrons.

2. Experimental techniques

The final nuclei $^{165,167}\text{Yb}$ were produced in $^{152,154}\text{Sm}$ ($^{17,18}\text{O}, \text{xn}$) reactions at beam energies of 80-84 MeV, using the $^{17,18}\text{O}$ beams of the Niels Bohr Institute tandem accelerator. The experiments consisted of γ -ray angular distribution, γ - γ coincidence and conversion electron coefficient measurements. Isotopically enriched (> 98%) metallic targets of ^{152}Sm and ^{154}Sm , mounted on ^{208}Pb backings were used for the measurements. All the measurements on ^{167}Yb were carried out with a 1.3 mg/cm^2 ^{154}Sm target on a 0.9 mg/cm^2 lead backing. A 2.5 mg/cm^2 thick ^{152}Sm target on 4.1 mg/cm^2 lead backing was used for γ -ray angular distribution and γ - γ coincidence measurements for ^{165}Yb , while a 1.2 mg/cm^2 ^{152}Sm target on a thinner (1.2 mg/cm^2) lead backing was used for the conversion coefficient measurement.

2.1. The nucleus ^{165}Yb

All studies of ^{165}Yb were performed in the $^{152}\text{Sm}(^{17}\text{O}, 4n)$ reaction at a beam energy of 80 MeV. The relative yields of various reaction products at this bombarding energy were $\approx 60\%$ ^{165}Yb , $\approx 40\%$ ^{164}Yb and very small amounts of ^{166}Yb and ^{162}Er .

For the measurements of the angular distribution of the γ -rays, two sets of singles γ -ray spectra were obtained simultaneously at 5 different angles between 0° and 90° . A single Ge(Li) detector and a Compton-suppressed Ge(Li) detector were used for the two sets respectively. These two detectors were mounted on a common turntable at right angles to each other. A third detector placed below the target served as a monitor detector. With this set-up it was possible to deduce the

angular-distribution coefficients. For γ -rays containing unresolved components of isotropic contribution from γ -rays due to radioactive nuclei only the angular anisotropy could be determined. Efficiency calibrations at various angles were performed with a radioactive ^{152}Eu source placed at the target position. The angular-distribution coefficients were obtained by fitting the normalised peak intensities to the expression $W(\theta) = A_0 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)$. The results from the two sets of data are consistent and are summarized in table 1. The energy calibration was performed by recording a singles γ -ray spectrum at 90° along with the spectrum from a ^{152}Eu source placed near the target.

An experimental set-up consisting of five Compton-suppressed Ge(Li) detectors was used for the coincidence studies. The details of the set-up will be published elsewhere¹⁶⁾. This set-up reduces the background by about a factor of 3, thereby making it possible both to identify weak transitions in the gated spectra and to gate on weak transitions. The reduction in the background resulted in an almost five-fold decrease in the amount of data to be handled. Furthermore, the use of five detectors renders it feasible to run a coincidence experiment with a reasonable counting rate¹⁶⁾. In our experiment, the gains of the amplifiers of the Ge(Li) detectors were matched. In all, about 22 million Compton-suppressed coincidence events were accumulated on tapes for off-line analysis. The tapes were sorted for all possible combinations of detectors, and the resultant spectra, after background subtraction, were added together. Examples of coincidence spectra are shown in fig. 1.

A 1-fold conversion electron spectrum gated by a multiplicity filter was acquired at 55° with a mini-orange spectrometer with a cooled Si(Li) detector. A 1-fold γ -ray spectrum gated by the same multiplicity filter was acquired simultaneously at -125° . The conversion coefficients were normalised to the $\alpha_K(E2)$ values of the 605.5 and 674.8 keV transitions in ^{165}Yb .

2.2. The nucleus ^{167}Yb

The coincidence run for ^{167}Yb was made with a 80 MeV ^{17}O beam on a ^{154}Sm target, using three large volume Ge(Li) detectors and one planar Ge(Li) detector, together with four large volume NaI(Tl) detectors serving as a multiplicity filter. The gains of the three large volume Ge(Li) detectors were matched. About 200 million two- or higher-fold coincidence events, in which at least two of the detectors triggered were Ge(Li) detectors, were accumulated on magnetic tapes for off-line analysis. Examples of coincidence spectra are shown in fig. 2. The reaction at this bombarding energy resulted in almost equal amounts of ^{166}Yb and ^{167}Yb . The data for ^{166}Yb , extracted from this experiment were a valuable aid in the interpretation of the coincidence data obtained in a previous run ¹¹⁾ for ^{166}Yb . This was mainly due to the complete absence of the contaminant lines from ^{165}Yb in this experiment in contrast to the previous experimental study of ^{166}Yb .

The $^{154}\text{Sm}(^{18}\text{O},5n)^{167}\text{Yb}$ reaction at a beam energy of 84 MeV was used for the angular distribution coefficient measurement. Singles γ -ray spectra were obtained at 9 different angles between -90° and 90° , the reaction being monitored by a detector at 155° . The efficiency calibrations at various angles were performed with ^{152}Eu and ^{177}Lu sources placed at the target

position. Energies of the γ -rays were determined by recording simultaneously at 90° the γ -rays from the reaction and γ -rays from ^{152}Eu and ^{137}Cs sources. The results of these measurements are summarised in table 2.

3. Construction of the level schemes

3.1. The nucleus ^{165}Yb

High-spin states in ^{165}Yb have previously been studied by Riedinger et al.¹⁷⁾ and Richter et al.¹⁸⁾. The level scheme of ^{165}Yb , as deduced from the present studies, is presented in fig. 3. The spin and parity assignments are based on the angular-distribution and conversion-coefficient measurements. All the transitions within a band are found to be of stretched E2 type.

Based on the systematics of Nilsson orbitals in this region, the ground state of ^{165}Yb has been classified as $[523] 5/2^-$ (see sect. 4.2). The ground-state band has been observed up to a spin of $53/2^-$ in the present study. The ordering of the transitions is based on the coincidence relationships and the identification of six interband transitions connecting this band to the unfavoured member of the band based on the $i_{13/2}$ neutron orbital. This order differs from those given in refs.^{17,18)}, which were obtained from the singles γ -ray intensities and from coincidence relationships in spectra obtained by gating on low-lying transitions. In the present study, on the other hand, it has been possible to gate on high-lying transitions (cf. fig. 1). A 627.6 keV transition, which probably feeds the level at 4472.7 keV, is weak and its multipolarity could not be deduced from the

present studies.

The favoured sequence of states based on the $i_{13/2}$ shell model orbital forms the yrast states and is most strongly populated. Although the 39 keV $9/2^+ \rightarrow 7/2^-$ transition, which was reported in refs.^{17,18)}, has not been observed in the present study, the relative positions of the levels, as deduced from the identification of interband transitions connecting the high-spin states, lend support to its existence. On the basis of results of e^- - γ coincidence experiment, Richter et al.¹⁸⁾ assigned the 804.6 keV γ -ray as a $45/2^+ \rightarrow 41/2^+$ transition. However, the present data shows that this transition feeds the $25/2^+$ level. The 728.1 keV transition is a self-coincident doublet. A weak line at 733 keV is found to be in coincidence with all the members of the cascade 206, 322, ..., 728 and its intensity relative to the low-lying members of the cascade increases as one gates higher up in the cascade. Moreover, the intensity of this line in the spectrum gated by the 728.1 keV line is almost twice as much as that in the spectrum gated by the 675 keV line. Based on these facts, we arrived at the sequence 728.1, 728.1, 733. Based on the measured angular distribution coefficients and the conversion coefficient $\alpha_K = 7(2) \cdot 10^{-3}$, both the 728.1 keV transitions are assigned to be of the stretched E2 type. The 733 keV transition is tentatively assigned as the $(49/2^+) \rightarrow 45/2^+$ transition. The unfavoured members of the positive parity band have been observed up to spin $39/2^+$. The 704 keV γ -ray assigned by Richter et al.¹⁸⁾ as the $35/2^+ \rightarrow 31/2^+$ transition is found to feed the $23/2^+$ level.

A negative parity band based on the level at 1979.2 keV has been assigned to ^{165}Yb . This band is joined by means of four interband transitions to the positive parity band. Although the 804.6 keV transition is the strongest γ -line depopulating this band, the measured angular distribution coefficients of this line entail considerable uncertainties due to the presence of the Doppler broadened 803 keV line originating from Coulomb excitation of ^{206}Pb found in the beam-stop. Nevertheless, the measured angular distribution coefficients of all the interband transitions, combined with the conversion coefficient $\alpha_K < 4 \cdot 10^{-3}$, of the 804.6 keV line establish the spin sequence and parity of this band. The level at 1516 keV may be a low-spin continuation of this band.

3.2. The nucleus ^{167}Yb

Lindblad¹⁹⁾ studied the nucleus ^{167}Yb using the $(\alpha, 3n)$ reaction. The level scheme for ^{167}Yb , as constructed from the present studies, is presented in fig. 4. The low-spin part of the level scheme is in agreement with that of ref.¹⁹⁾. The ground state of ^{167}Yb is classified as $[523] 5/2^-$ from the systematics of the Nilsson levels in this region (see sect. 4.2). The ground-state band has been extended up to a spin $49/2^-$ from a known $25/2^-$ state. The favoured and the unfavoured members of the band based on the $[642] 5/2^+$ quasiparticle state have been extended up to spins $53/2^+$ and $43/2^+$, respectively, from $33/2^+$ and $31/2^+$ known from ref.¹⁹⁾. We have furthermore identified several interband transitions depopulating members of the negative parity band. The low energy M1/E2 transitions between the two different signatures of the positive parity band are based on the coincidence data.

The nucleus ^{167}Yb has recently been studied in Brookhaven²⁰⁾ using a Be beam and a similar level scheme has been established. Although some of the transitions belonging to a band based on $[505] 11/2^-$ as proposed by Lindblad¹⁹⁾, are seen in the present work, no conclusions could be drawn about this band due to the weakness of these transitions. It is to be noted that the levels of the $[505] 11/2^-$ band are expected to lie high above the yrast levels of similar spins, and, consequently, this band would be faintly populated in heavy-ion reactions, if populated at all.

4. Discussion.

4.1. Transformation to e' versus $\hbar\omega$ representation

It is generally accepted that the decay sequences established for medium- and heavy-mass rare-earth nuclei are composed of cascades along a series of rotational bands each based on a particular configuration. In order to study the effect of rotation on independent-particle motion in a deformed nucleus, it is convenient to transform the spectrum of energy levels contained in the decay scheme (e.g. see figs. 3-5) to excitation energies in a rotating "intrinsic" frame (Routhians, e') as a function of the angular frequency ($\hbar\omega \approx E_\gamma/2$ for $\Delta I = 2$). In the e' versus $\hbar\omega$ representation it is possible to obtain information on the energy contribution to the nucleus in the intrinsic frame, from the rotational motion, since the Hamiltonian h^ω for independent-particle motion in a rotating deformed nucleus is:

$$h^\omega = h^0 - \omega j_1 \quad (1)$$

h^0 is here the quasiparticle Hamiltonian in a static, deformed field (e.g. the field of the Nilsson model), ωj_1 is the Coriolis and centrifugal term with j_1 being the projection of the single particle angular momentum on the axis of rotation (the 1-axis), taken to be perpendicular to the symmetry axis. Such information is available for the nuclear configuration corresponding to each rotational sequence in the decay scheme.

The detailed prescription for the transformation to excitation in a rotating frame and to $\bar{h}_\omega$ is given in the literature (see e.g. ref. 6) and, therefore, will not be given explicitly in this paper. The procedure lends to a subtraction of the rotational energy, i.e. ωI_1 (I_1 is the component of the total angular momentum along the axis of rotation), from the excitation energy. In order to compare the intrinsic-frame excitation energies between different nuclei and also with the results of calculations, it is convenient to establish a reference frame. Two choices of reference frame are in common use: the even-even nucleus ground-state configuration⁶⁾ and the yrast configuration²¹⁾ of the even-even nucleus (see fig. 6). For odd-N or odd-Z nuclei the Routhians are referred to the appropriate reference configuration of the neighbouring even-even nucleus and the pairing-correlation parameter Δ is added⁶⁾. However, technical problems are associated with both choices of reference frames. The ground-state band moment of inertia is not constant at the lowest $\bar{h}_\omega$ and this band is not known at higher $\bar{h}_\omega$. Therefore, for the ground-state reference it is necessary to choose an appropriate parameterized reference as a function of $\bar{h}_\omega$ to approximate the zero-quasiparticle ground-state configuration. The choice can then be a band with a variable moment

of inertia²²⁾, as described by the Harris formula²³⁾

$$\mathcal{J} = \mathcal{J}_0 + \omega^2 \mathcal{J}_1 \quad (2)$$

with $\mathcal{J}_1 = 90 \text{ MeV}^{-3} \hbar^4$ and $\mathcal{J}_0 = 27.8, 29.8$ and $31.8 \text{ MeV}^{-1} \hbar^2$, respectively for ^{165}Yb , ^{166}Yb and ^{167}Yb . These parameters, which are similar to those used for lighter Yb isotopes^{4,24)}, are a compromise between the values necessary to produce constant alignment in the ground-state band ($\mathcal{J}_1 \approx 125 \text{ MeV}^{-3} \hbar^4$ in ^{166}Yb) and in the yrast sequence above the lowest-frequency band crossing, the S-band²⁵⁾, ($\mathcal{J}_1 \approx 70 \text{ MeV}^{-3} \hbar^4$). The use of such an average reference frame results in a slight increase in the alignment with increasing frequency in the ground-state band and a small decrease of i with $\hbar\omega$ in the S-band. The smooth variation of the Harris parameters with neutron number ($\mathcal{J}_1$ constant and $\mathcal{J}_0$ only slightly N dependent) makes it possible to discuss the rotational effects on quasineutron states in neighbouring isotopes.

Problems associated with the extrapolation of the ground-state reference frame to higher $\hbar\omega$ can be circumvented by referring the intrinsic-frame excitation energies to the yrast band. The yrast configuration of even-even nuclei, however, is not necessarily appropriate for the neighbouring odd-mass isotopes and isotones. For example, a difference in pairing and interaction strengths between odd- and even- N (or Z) neighbours will produce changes in the reference appropriate for odd- and even- N (or Z) systems. Such problems will be discussed in subsection 4.4 where experimentally constructed Routhians are compared directly with calculated values.

Information about alignment, i , also is contained in the

e' vs $\hbar\omega$ plots with

$$i = \sum j_1 = - \frac{de'}{d\omega} \quad (3)$$

(From eq. 1 and $e' = \langle h^\omega \rangle$). It is often convenient to plot i vs $\hbar\omega$, perhaps because of the similarity of such a presentation of the data with the familiar "backbending" plot. The alignments are also shown in fig. 6 as a function of $\hbar\omega$ for the yrast sequence of ^{166}Yb referred to both the ground-state band and the yrast references. Near $\hbar\omega_c$, the angular frequency of the band crossing, the excitation energy of the yrast sequence is double-valued for a particular $\hbar\omega$ ("backbending"). It is, therefore necessary to define which branch of the yrast sequence that is to be taken as the reference : for $\hbar\omega < \hbar\omega_c$ the ground-state band is used as reference; for $\hbar\omega > \hbar\omega_c$ the S-band is taken as reference. ($\hbar\omega_c$ is defined as the angular frequency where the ground-state band and S-band Routhians cross.) The appearance of a crossing between the weakly-interacting bands in e' and i plots referred both to the ground-state and the yrast configurations are shown in fig. 6.

Since the present work is confined to reasonably low values of $\hbar\omega$, where the extrapolation of the ground-state configuration is reasonable, the data will usually be referred to a parameterized ground-state configuration (eq. 2.). For example, the level scheme information for $^{165,166,167}\text{Yb}$ is shown transformed to the rotating frame and referred to the ground-state configuration in fig. 7. In ^{167}Yb , however, where there are strong interactions between the quasiparticle configurations, it is more convenient to choose a yrast reference (see subsection 4.4).

4.2. The spectrum of single-quasineutron states in $^{165,167}\text{Yb}$

Three bands are known, in both ^{165}Yb and ^{167}Yb which can be interpreted as rotational bands based on single-quasineutron intrinsic configurations: the ground-state band with $^{\dagger}(\pi, \alpha)_n = (-, +)_1$ and the favoured and unfavoured portions of the yrast band with $(\pi, \alpha)_n = (+, +)_1$ and $(+, -)_1$ respectively. The systematics of the single-quasiparticle state Routhians are as expected from the Nilsson states near the Fermi surface (see fig. 8). The $K^{\pi} = 5/2^{-}$ ground-state band in both odd-N nuclei is expected to correspond to the $5/2^{-}$ [523] Nilsson orbit at $\hbar\omega = 0$, which is expected to lie just above the Fermi surface in ^{165}Yb and just below the Fermi surface in ^{167}Yb . This Nilsson orbit is based on a dominantly $h_{9/2}$ shell-model state; therefore, because of the relatively large Ω when compared to j , this configuration is expected to obtain only a small alignment when rotated. In contrast, the yrast bands are

[†] The rotational configurations are labelled by the conserved quantum numbers of the corresponding intrinsic quasiparticle configurations, parity, π , and signature, α , (+ or - corresponds to $\alpha = +\frac{1}{2}$ or $-\frac{1}{2}$, when $\alpha = 1$ or 0 it is explicitly stated). The n designates that this configuration is the n^{th} such configuration with these quantum numbers. A superscript S is added, $(\pi, \alpha)_n^S$, to multi-quasiparticle states to designate the seniority of the configuration. Note that the π of a multiple-quasiparticle configuration is the product of those of the constituent quasiparticles, whereas the α of the multiple-quasiparticle configuration is the sum of the α 's of the constituent quasiparticles.

expected and observed to have larger rotational alignments. These bands in both ^{165}Yb and ^{167}Yb are based on the $(+,+)_1$ and $(+,-)_1$ intrinsic configurations that at $\bar{h}_\omega = 0$ correspond to the $5/2^+$ [642] Nilsson configuration which involves the larger j of the $i_{13/2}$ neutrons. Furthermore, the highly-alignable $3/2^+$ [651] and $1/2^+$ [660] Nilsson configurations are sufficiently close to the Fermi surface (see fig. 8) to mix into the yrast configurations at higher $\bar{h}_\omega$. Indeed the sizable energy splitting between the Routhians corresponding to the different signatures of the yrast configuration, i.e. $(+,+)_1$ and $(+,-)_1$, is a measure of the $\Omega=1/2$ component in the wave function. The decrease in the observed signature splitting between ^{165}Yb and ^{167}Yb (see fig. 7), therefore, is a result of the shift of the Fermi surface away from the low- Ω orbits with increasing neutron number.

4.3. Construction of multiple-quasineutron states from the spectrum of single-quasineutron states

The single-quasineutron states such as the three observed experimentally in $^{165,167}\text{Yb}$, represent the "building blocks" for the construction of multiple-quasineutron states. From the energies of these states in the intrinsic system, e'^s , it is possible to construct experimental estimates of excitation energies as a function of $\bar{h}_\omega$ for multiple-quasiparticle states. For example the e'^s corresponding to the lowest expected two-quasiparticle, positive-parity configuration, $(+,0)_1^2$, and the two lowest two-quasiparticle, negative-parity configurations $(-,1)_1^2$ and $(-,0)_1^2$ in ^{166}Yb can be constructed from the known single-quasineutron configurations $((+,+)_1,$

$(+, -)_1$ and $(-, +)_1$ in $^{165,167}\text{Yb}$ (see fig. 9), $(+, 0)_1^2 = [(+, +)_1 \times (+, -)_1]_1^2$, $(-, 1)_1^2 = [(+, +)_1 \times (-, +)_1]_1^2$ and $(-, 0)_1^2 = [(+, -)_1 \times (-, +)_1]_1^2$. Two of the constructed two-quasineutron configurations, $(+, 0)_1^2$, i.e. the S-band, and $(-, 1)_1^2$, the lowest negative-parity band, are known in ^{166}Yb . Similarly, one three-quasineutron configuration, $(-, +)_1^3 = [(+, +)_1 \times (+, -)_1 \times (-, +)_1]_1^3$, can be constructed from the known configurations (fig. 9), and be compared with a known band, the ground-state band in odd-A nucleus above the observed band crossing. From the comparison of multiple-quasiparticle states constructed from experimental single-quasiparticle states and the corresponding experimental multiple-quasiparticle states, it can be ascertained whether strong $\hbar\omega$ dependent or configuration dependent residual interactions exist between the constituent quasineutrons in the multiple-quasineutron configurations. A premise of the cranked shell model⁶⁾ is that such residual interactions between quasiparticles are weak.

It also is possible to obtain information on the neutron pairing-correlation parameter, Δ_n , from the comparison of the absolute excitation energies of the constructed and experimental multiple-quasineutron Routhians. Since the single-quasiparticle levels usually are referred to the ground-state configuration of the neighbouring even-even nuclei (see subsection 4.1), it is necessary⁶⁾ to include, as a constant factor, Δ_n in the odd-A Routhians. Instead of including, for example, the odd-even mass difference as an estimate of Δ_n into the odd-A Routhians, we have chosen to keep Δ_n as a parameter and plot $e' - \Delta_n$ for the odd-A systems. Then the energy difference between the constructed two-quasineutron systems,

$e'_{2\text{ qp}} - 2\Delta_n$, and the experimental values in the neighbouring even-even systems, $e'_{2\text{ qp}}$ will give a measure of Δ_n (see figs. 9 and 10). The values of Δ_n obtained from such a comparison will be labelled Δ_n^{ce} to emphasise that they were obtained as a difference between two-quasineutron Routhians, constructed as a sum of "experimental" single-quasineutron Routhians and "experimental" two-quasineutron Routhians. From a similar comparison of the constructed and the experimental three-quasineutron states a measure of Δ_n also is obtained, since Δ_n enters the constructed three-quasineutron states three times (once in the $e' - \Delta_n$ for each quasineutron - see fig. 9) and only once in the construction of the experimental Routhian for the three-quasineutron state.

Constructed two-quasineutron Routhians for the $(+,0)_1^2$ and $(-,1)_1^2$ states are compared to the experimental ones for ^{166}Yb in the left-hand side of fig. 10. In the construction of the two-quasineutron Routhians average values of the appropriate single-quasineutron Routhians in ^{165}Yb and ^{167}Yb have been used. Such an averaging should remove, to first order, effects, which vary smoothly with neutron number. In fig. 10 the constructed two-quasineutron Routhians (i.e. $e'_{2\text{ qp}} - 2\Delta_n$) have been shifted up by a constant factor of $2\Delta_n^{\text{ce}} = 1.98\text{ MeV}$ in order to reproduce the experimental values. Both the slope (i.e. the alignment) and the energy splitting of the experimental Routhians for the lowest positive- and negative-parity two-quasineutron configurations are reproduced by Routhians constructed as a sum of the Routhians of single-quasineutron configurations. Such an agreement between the

constructed and the experimental two-quasineutron Routhians indicates that a residual interaction between the two unpaired quasineutrons is not strongly dependent upon the angular frequency or the quasiparticle configuration. A residual interaction independent of $\hbar\omega$ and configuration, however, is absorbed in the extracted value of the neutron pairing-correlation parameter, and, therefore, can be extracted by comparison with the neutron odd-even mass difference, Δ_n^{oe} , or the value of Δ_n which reproduces¹⁵⁾ the ground-state band-S-band crossing, Δ_n^{CSM} . For ^{166}Yb , the value of $\Delta_n^{oe} = 0.99$ MeV is somewhat less than $\Delta_n^{oe} = 1.140$ MeV or $\Delta_n^{CSM} = 1.14 \pm 0.03$ MeV, indicating an attractive interaction of about 300 keV between the two unpaired quasineutrons in these configurations. A large portion of the n-n interaction is just the "blocking" of the contributions to pairing by the unpaired quasineutrons. The n-n residual interaction can be compared with the residual proton-neutron interaction estimated²⁶⁾ to be about 120 keV from the mass difference between odd-odd and even-even nuclei and the sum of Δ_n^{oe} and Δ_p^{oe} . The reduced value of the p-n residual interaction compared with the n-n residual interaction reflects the small pairing between protons and neutrons in this mass region where protons and neutrons are filling different major shells.

The constructed three-quasineutron Routhians for the $(-,+)_1^3$ configuration ($=e'(+,+)_1 + e'(+,-)_1 + e'(-,+)_1$) also are compared to the Routhians of the ground-state bands of $^{165,167}\text{Yb}$ above the band crossing. A smaller alignment is observed in the three-quasineutron configurations of both nuclei than is expected from the experimentally constructed Routhians. A possible explanation is that when three-quasineutron orbits

near the Fermi surface are occupied (thereby "blocking" their contribution to pairing), the pairing is sufficiently reduced to decrease the alignment. Cranked shell-model calculations do indicate that a decrease in alignment is associated with decreased pairing. Therefore, the present agreement in alignments for constructed and experimental two-quasineutron states together with the deviation for the three-quasineutron states would indicate a significant decrease in Δ_n for three-quasineutron configurations when compared to two-quasineutron configurations. Since there is a deviation between the slopes of the constructed and the experimental three-quasineutron Routhians, it is not possible to obtain an estimate of Δ_n from the energy difference between these Routhians.

4.4. Comparison with cranked shell-model calculations

In the mass region, where the Fermi surface is near the low- Ω $i_{13/2}$ neutron orbits, the band-crossing frequency, $\hbar\omega_c$, corresponding to the alignment of the first pair of neutrons, is controlled by a rotational aligned orbit near to the Fermi surface which is particularly sensitive to the neutron pairing-correlation parameter^{15)†}. From the $\hbar\omega_c$ of the band

† This is not necessarily always the case, as is shown for the light Os nuclei²⁷⁾, where low-frequency band crossings are controlled by rotational-aligned orbits sufficiently distant from the Fermi surface at low- $\hbar\omega$, so that the energy of the orbit relative to the Fermi surface ($\epsilon_v - \lambda$) is an important component in the quasiparticle energy

$$E_v = \sqrt{\Delta^2 + (\epsilon_v - \lambda)^2} \quad (4)$$

crossing in the ground-state band of $^{165,167}\text{Yb}$ it, therefore, is possible to obtain an estimate of Δ_n which should be appropriate for other band crossings between one- and three-quasineutron configurations. (The parity, $\pi=-$, of the ground-state band assures that none of the $i_{13/2}$ neutron configurations, $\pi=+$, are "blocked"). The procedure then is to take this value of Δ_n together with deformation parameters, ϵ_2 and ϵ_4 , from the systematics predicted by the Lund group^{9,28)} and the appropriate position of the Fermi surface, λ , to reproduce the neutron number, and to calculate the spectrum of single-particle states in the rotating intrinsic frame. The results of such cranked shell-model (CSM) calculations are shown in fig. 11.

It is possible to directly compare these predicted quasiparticle levels with the experimental Routhians constructed (see sect. 4.1) from the decay scheme information. However, if the "extrapolated" ground-state configuration is taken as the "reference" at all angular frequencies (as was explicitly assumed in the previous sections), it is necessary to reconstruct the pure quasineutron states in the region where there is an interaction between the calculated states. The technique described in refs.^{6,29)} have been used to obtain the pure quasineutron states in the interaction region and the appropriate resulting theoretical and "experimental" Routhians for ^{165}Yb are compared in fig. 12. At angular frequencies below that of the trajectory crossings, the alignment (i.e. slopes of the Routhians with respect to $\hbar\omega$) and the relative excitation energies of the lowest positive- and negative-parity trajectories ($(+,+)_1$ and $(-,+)_1$) are well

reproduced. In the construction of the experimental Routhian the value $\Delta_n \equiv 0.87$ MeV, necessary to reproduce the band crossing in the ground-state band¹⁵⁾, has been assumed. The energy splitting between the two signatures of the positive-parity trajectories, $(+,+)_1$ and $(+,-)_1$, is greater than predicted, probably indicating too large of an $\Omega = 1/2$ component mixed into the wavefunctions of these configurations. A similar discrepancy has been observed for several other rare-earth nuclei⁶⁾. The $\pi\omega$ of the alignment of the first two quasineutrons, $\pi\omega_1$, which corresponds to the crossing of the negative-parity single- and three-quasineutron trajectories, has been fixed in the calculations to reproduce the experimental value by the appropriate choice of Δ_n ¹⁵⁾. For $\pi\omega > \pi\omega_1$ a larger alignment is predicted for both negative-parity, three-quasineutron configurations, $(-,+)_1^3$, and $(-,-)_1^3$ than observed. Such a reduction of the alignment for the $(-,+)_1^3$ configuration relative to the appropriate experimentally constructed three-quasineutron configuration is also observed (see fig. 9) and a reduced pairing in the three-quasineutron configuration has been suggested (subsection 4.3) as a possible explanation. The alignment of the three-quasineutron configurations can be reproduced in CSM calculations if the pairing-correlation parameter is reduced by 25% from the value of Δ_n^{CSM} obtained from one- and three-quasineutron band crossing frequencies. Therefore, a 45-50% pairing reduction is indicated when the pairing contributions of the $(-,+)_1$, $(+,+)_1$ and $(+,-)_1$ configurations are "blocked". Even though the alignments of these configurations are not in agreement with CSM predictions, the energy

splitting between the two signatures does agree with the calculations.

Band crossings are also predicted in the positive-parity decay sequence (see fig. 12), corresponding to the alignment of a different pair of $i_{13/2}$ quasineutrons than those responsible for the lower frequency alignment in the negative-parity band and in the yrast band of the neighbouring even-N isotopes. The crossing in the band corresponding to the $(+,+)_1$ configuration, however, is observed ≈ 50 keV higher in Eu than predicted in the calculations based on the Lund deformation systematics^{9,28)}. It, of course, is possible to increase the frequency of this band crossing in CSM calculations by an arbitrary increase in the pairing-correlation parameter. However, to reproduce the observed crossing frequency, it is necessary to increase Δ_n by about 35% with respect to the value used to reproduce the lower-frequency crossing in the negative-parity band. Such an increased value of Δ_n is as large as that derived from the ground-state band-S-band crossing in the neighbouring even-N isotopes¹⁵⁾. It is difficult to understand in a phenomenological way how the occupancy of certain single-particle configurations in odd-N nuclei would significantly reduce Δ_n while others would not affect $\Delta_n^\dagger$. Therefore, it is felt that factors other

[†] Recent calculations³⁰⁾ do suggest that the reduction in pairing in odd-N nuclei is dependent on the configuration of the unpaired single particle. For neutron levels in rare-earth nuclei, pairing is reduced more for the negative-parity states than for the positive-parity states and for configurations with smaller signature splitting. Such effects might play a role in explaining the observed discrepancy in the band crossing frequency in the

than pairing must play a role in the problems of predicting the crossing frequency of the positive-parity band in ^{165}Yb . Indeed the observed crossings in both the negative- and the positive-parity bands of $^{161,163}\text{Yb}$ are reproduced simultaneously in CSM calculations^{4,12,24)}, while those in ^{165}Yb are not. The source of the discrepancy in ^{165}Yb is not understood. For example, it is difficult to alter significantly the $\bar{\epsilon}_0$ difference between the predicted crossings for the negative- and the positive-parity bands by small changes in the ϵ_2 and/or ϵ_4 deformations. (Such deformation changes alter the position of the Nilsson states near the Fermi surface.) The frequency of the crossing in the favoured positive-parity band (which corresponds to the exchange of the roles of the $(+,+)_1$ and $(+,+)_2$ trajectories -- see fig. 11) represents a more stringent test of the CSM than the lowest-frequency band crossing (i.e. that observed in the negative-parity band). The $(+,+)_1 - (+,+)_2$ crossing is sensitive to the quasiparticle energy, alignment, and the interaction of the $(+,+)_2$ trajectory as well as that of the $(+,+)_1$ trajectory. The $(+,+)_2$ trajectory is derived from a Nilsson orbit that is not so near to the Fermi surface, and it interacts with other more highly aligned orbits which are more distant from the Fermi surface (see fig. 11). Therefore, not only the relative positions of orbits, but also their energy separation from the Fermi surface, i.e. $\epsilon_0 - \lambda$ (see eq. 4), is important in predicting the

positive-parity band in ^{165}Yb . However, the observed signature splitting between positive-parity states in ^{161}Yb and ^{163}Yb are larger than in ^{165}Yb ; therefore, superficially such an effect would seem to be largest in the lighter odd-N Yb isotopes where the band crossing is predicted at the correct frequency²⁴⁾.

frequency of the $(+,+)_1 - (+,+)_2$ and higher frequency crossings. The strength of the interaction of the $(+,+)_1$ orbit with the vacuum (i.e., with its negative-energy conjugate partner⁶⁾) which produces the change of slope of this level at the frequency of the band crossing in the negative-parity bands (see fig. 11), also affects the position of the $(+,+)_1 - (+,+)_2$ band crossing.

When the interaction between the quasiparticle trajectories is strong, it becomes difficult to reconstruct the "pure" quasiparticle trajectories in the interaction region. In the case of ^{167}Yb (fig. 11), where there are two strongly interacting trajectory crossings closely spaced in angular frequency (corresponding to the alignment of the first and the second pair of $i_{13/2}$ neutrons), it is particularly difficult to reconstruct "pure" trajectories. Such problems can be circumvented by referring the experimental Routhians to the yrast band in the neighbouring even-N isotope. Then the experimental Routhians can be compared directly (see fig. 13) to the calculated Routhians. In fact, it has been suggested²¹⁾ that such an approach may be superior, since the interaction at a crossing is never zero and at large angular frequencies the spectrum of quasiparticle levels becomes complicated.

Several practical problems are encountered in referring the odd-N experimental Routhians to the yrast band of the neighbouring even-N isotope. Ideally the average Routhian of the yrast line from the even-N isotopes with one less and one more neutron can be constructed as a function of $\hbar\omega$ and

subtracted as a reference from the odd-N isotope of interest. It is known, however, that the frequency for the alignment of the first pair of $i_{13/2}$ neutrons is different in odd-N and even-N isotopes¹⁵⁾. Therefore, it is necessary to shift the reference or the experimental vacuum in $\hbar\omega$ so that the crossing frequency of the reference coincides with that in the isotope of interest. (Obvious problem will be encountered if the angular frequency range of interest extends through several yrast band crossings which require different angular frequency shifts). Besides the shift in the alignment frequency for the first pair of $i_{13/2}$ neutrons, a shift in the magnitude of the alignment associated with this pair of neutrons apparently is observed between the two-quasineutron and the three-quasineutron configuration, presumably also the result of the reduced pairing associated with the larger number of aligned quasiparticles (see section 4.3 and ref. 24)). Another problem, which must be considered when applying the experimental yrast line as a reference for the neighbouring isotope, is the variation between neighbouring isotopes of the interaction between the constituent bands of the yrast configuration^{9,10,32)}. The appropriate treatment for such change in alignment and in the interband interaction strength between the neighbouring even- and odd-N isotopes is not a priori obvious. The approach, therefore, is to examine for ^{165}Yb the comparison between the experimental and predicted Routhians for both choices of reference frames and then to consider the case of ^{167}Yb where only the reference to the yrast band is appropriate.

When the experimental Routhians are referred to the yrast configuration the crossing in the negative-parity bands

in $^{165,167}\text{Yb}$, which corresponds to the low frequency $i_{13/2}$ neutron alignment, should disappear (compare figs. 12 and 13). This alignment also appears in the even- N yrast band reference. Therefore, a test of the reference frame depends on whether the resulting Routhians of the negative-parity bands are smooth in the region of the low-frequency band crossing. A "glitch" appears in the experimental Routhian of the $(+,+)_1$ band[†] in ^{165}Yb at the crossing frequency and the slope of both the negative-parity bands, $(-,+)_1$ and $(-,-)_1$ is less than predicted for $\hbar\omega > \hbar\omega_c$ (see fig. 12). These features presumably are associated with the problem of referring the Routhians to the yrast bands of even- N neighbour with pairing correlations and interband interactions which are not completely appropriate to ^{165}Yb . The discrepancy between the predicted and the observed alignments of the negative-parity states of ^{165}Yb (see fig. 12) appears as a slope change of the experimental Routhian in the yrast-reference representation (see fig. 13). The difference between the predicted and the observed energy splitting of the $(+,+)_1$ and $(+,-)_1$ configurations (signature splitting) and the discrepancy in the crossing frequencies for these positive-parity band both can be observed (fig. 13) in the yrast-

[†] In the representation of the quasiparticle relative to the yrast configuration, the configurations are labelled by the non-yrast excited quasiparticles²¹⁾. For examples, the ground-state bands of $^{165,167}\text{Yb}$ will be $(+,+)_1$ both below and above the band crossing, since the $i_{13/2}$ neutrons also become aligned in the reference.

-reference representation, even though a slope change is introduced into the Routhians, the result of the ground-state band-S-band crossing in the even-N yrast reference.

The ^{167}Yb experimental Routhians, shown in fig. 12, are referred to the yrast band of $^{168}\text{Yb}^{20,33}$. A constant value of $E_0 = 0.79$ MeV has been included in the Routhian. This value corresponds to $\Delta_n = 0.745$ MeV plus a contribution from $\epsilon_0 - \lambda$ (see eq. 4), which accounts for the fact that the Fermi surface in ^{167}Yb is located in a gap in the Nilsson levels (fig. 8). Had the ^{166}Yb yrast band, with its weak ground-state band-S-band interaction, been used as a reference for ^{167}Yb , with its strong interaction between the ground-state band and its crossing band, then a pronounced "glitch" would have appeared in the negative-parity band at the crossing frequency. Similarly, the large S-band alignment in ^{166}Yb would have led to a slope change in the ^{167}Yb negative-parity band above the band crossing frequency. With the reasonably smooth Routhians of the negative-parity band of ^{167}Yb in the frequency region of the $i_{13/2}$ neutron alignment and the agreement between the experimental and the predicted Routhians for this band, we proceed to the discussion of the more structured Routhians for the positive-parity configurations of ^{167}Yb with some conviction that the ^{168}Yb yrast configuration is a reasonable reference for ^{167}Yb . The Routhians of the positive-parity are at low E_0 lower in excitation energy than predicted, indicating either that the predicted energy separation between the $5/2^-$ [523] and the $5/2^+$ [642] Nilsson configurations is too great or that the Fermi surface should be closer to the $7/2^+$ [633] Nilsson state than to the

$5/2^+$ [642] state (see fig. 8). Similar to ^{165}Yb and other⁶⁾ odd-N rare-earth nuclei, the signature splitting between the $(+,+)_1$ and the $(+,-)_1$ configurations is observed to be larger than predicted. Contrary to the case of ^{165}Yb , the crossing in the $(+,+)_1$ band, corresponding to the alignment of the second combination of $i_{13/2}$ neutrons[†] (i.e. the exchange of character of the $(+,+)_1$ and the $(+,+)_2$ configurations²¹⁾ is close to the predicted frequency. This crossing, which corresponds to the change in slope of the $(+,+)_1$ Routhian at $\hbar\omega \approx 0.32$ MeV, is characteristic of strongly interacting configurations in agreement with predictions. The band crossing in the $(+,-)_1$ band, corresponding to an exchange in character of the $(+,-)_1$ and the $(+,-)_2$ configurations, is not observed up to $\hbar\omega \approx 0.375$ MeV, whereas it is predicted at a lower angular frequency (see fig. 13). The alignment in the $(+,-)_1$ band apparently is starting to increase at the last observed transition, $\hbar\omega \approx 0.375$ MeV (see fig. 7). The crossings of the $(+,+)_1$ and $(+,-)_1$ bands are at different angular frequencies in contrast to the situation for the lighter Yb isotopes⁸⁾ where these crossings are found at nearly equal frequencies. This feature probably

[†] The alignment of the pair of $i_{13/2}$ neutrons which is responsible for the low-frequency band crossing in the negative-parity band of ^{167}Yb and the ground-state band-S-band crossing in the even-N isotopes is not allowed by the Pauli principle (i.e. "blocked") since the lowest even-parity quasineutron orbit $(+,+)_1$ is occupied.

is connected to the low- Ω components, with an associated large alignment, which mixes into the $(+,+)_1$ quasineutron for $N > 95$, thereby depressing the $(+,+)_2$ trajectory with respect to the $(+,-)_2$ trajectory (see fig. 11). For the lower-mass Yb isotopes, the highly aligned low- Ω trajectories are near the Fermi surface. Even though the CSM calculations give a qualitative description of the crossing frequencies and the interaction strengths in the $(+,+)_1$ band, the details of the Routhian are not reproduced (see fig. 13).

4.5. Interband M1 transitions

The interband M1-transition matrix elements connecting states in rotational bands based on the opposite signatures of high- j , low- Ω quasiparticle orbits are predicted³³⁾ to be strongly signature dependent even for small rotational frequencies. The M1 transitions between bands based on the $(+,+)_1$ and $(+,-)_1$ configurations in light odd- N Yb nuclei provide an excellent test of these predictions, since these bands are strongly populated in (H.I.,xn) reactions. In fact, such transitions in ^{161}Yb ^{4,34)} were used as the original example of this effect. The interband transitions between the $(+,+)_1$ and $(+,-)_1$ bands in $^{165,167}\text{Yb}$ provide an even more sensitive test of the signature-dependent rotational effect on the M1 transitions. Not only are more transitions observed in ^{167}Yb than in ^{161}Yb , but in ^{165}Yb the signature splitting in energy is such that the $I-1$ state in the $(+,-)_1$ band is nearly degenerate with the I state in the $(+,+)_1$ band (see fig. 3). This is exactly the condition for the M1-transition matrix elements for $(I+1, \alpha = -\frac{1}{2} \rightarrow I, \alpha = \frac{1}{2})$ transitions to approach zero, and for

that for the $(I, \alpha = \frac{1}{2} \rightarrow I-1, \alpha = -\frac{1}{2})$ transitions to have the maximum enhancement³³⁾. For example, $B(M1, 23/2^+ \rightarrow 21/2^+)$ should be very small and $B(M1, 21/2^+ \rightarrow 19/2^+)$ is expected to be large. In ^{165}Yb , the γ -ray energies of the $(I, \alpha = \frac{1}{2} \rightarrow I-1, \alpha = -\frac{1}{2})$ transitions in the yrast band are so small that these transitions cannot compete with the strongly-enhanced $I \rightarrow I-2$ transitions along the yrast band. The $(I+1, \alpha = -\frac{1}{2} \rightarrow I, \alpha = \frac{1}{2})$ transitions, which should be greatly hindered, however, are observed. In ^{167}Yb , where the signature splitting is smaller, both types of M1 transitions between the positive-parity bands are observed.

Even though no absolute transition rates have been measured, some information on the M1 matrix elements can be extracted by a comparison to the E2 strength which is assumed to follow the pattern of rigid rotation[†]. From the experimental branching ratios $\lambda = \Gamma_{\gamma}(I \rightarrow I-2) / \Gamma_{\gamma}(I \rightarrow I-1)$, a value of

$$\frac{B(M1)}{Q_0^2} = \frac{E_{\gamma 1}^2}{14.41} \cdot \left[\left(\frac{E_{\gamma 2}}{E_{\gamma 1}} \right)^5 \cdot \langle IK20 | I-2K \rangle^2 \cdot \frac{1}{\lambda} - \langle IK20 | I-1K \rangle^2 \right]$$

can be extracted. It is also possible to use the experimental values of the mixing ratios δ within the $I \rightarrow I-1$ transitions to determine the same ratio

$$\frac{B(M1)}{Q_0^2} = \frac{E_{\gamma 1}^2}{14.41} \cdot \frac{\langle IK20 | I-1K \rangle^2}{\delta^2}$$

In both expressions $E_{\gamma 1}$ and $E_{\gamma 2}$ correspond to the energies in keV for the $I \rightarrow I-1$ and the $I \rightarrow I-2$ transitions respectively.

[†] Rotational perturbations on $B(E2)$ values for the $I \rightarrow I-1$ transitions between the signature partners and for in-band $I \rightarrow I-2$ transitions are expected to be quite small³³⁾.

The data presented in fig.14 have been derived, assuming a value of $Q_0 = 7$ eb. For both nuclei studied, $K=5/2$ was used in extracting values of $B(M1)/Q_0^2$. Since the rotation is expected to mix lower K -values into the wave function, values of $K=3/2$ and $1/2$ were also applied and were found to increase the $B(M1)$ values extracted from the branching ratio λ , while the $B(M1)$ values obtained from the mixing ratio δ were found to decrease drastically. The experimental determination of δ involves a larger uncertainty than that of the λ -values, but, in order to bring the two extracted values of $B(M1)$ into agreement the average value of K has to be shifted to $\approx 1/2$ unit below $5/2$. The values presented in fig.14 have been derived from the branching ratios with this K -admixture taken into account. The effect is found to be largest on the highly retarded $B(M1)$ values in ^{165}Yb .

The agreement with the particle-rotor calculations³³⁾ for ^{165}Yb is excellent, but of course it would be very important to pin down the same values for the enhanced type of $M1$ transitions. For ^{167}Yb , the separation between the $B(M1)$ values for the transitions between the two signatures is observed, but in this nucleus the retardation is less, as is also expected, since the Fermi surface here lies further away from the low- Ω orbits of the $i_{13/2}$ configuration.

5. Summary

The nuclei $^{165,167}\text{Yb}$ are well-deformed nuclei with $\epsilon_2 \approx 0.25$ and very small ϵ_4 . The present study identifies the ground-state bands based on the $[523] 5/2^-$ Nilsson orbital to spins $53/2^-$ and $49/2^-$ for ^{165}Yb and ^{167}Yb respectively, thereby extending

the knowledge of the negative parity bands to well above the backbending region. The $\alpha = -\frac{1}{2}$ signature of the $[523] 5/2^-$ band has been identified in the case of ^{165}Yb above backbending. The favoured and the unfavoured members of the $i_{13/2}$ band have been established to high spin values, $49/2^+$ and $39/2^+$ for ^{165}Yb and $53/2^+$ and $43/2^+$ for ^{167}Yb , respectively.

The present study can be regarded as a test case for the Cranked Shell Model in a region of stable deformation. Routhians and alignments have been extracted from the experimental data. Experimental single-quasineutron Routhians have been used to construct two- and three-quasineutron Routhians. The $\bar{E}_0$ and configuration dependence of the constructed Routhians for two-quasineutron configurations in ^{166}Yb agree with the experimental data, suggesting that the residual interaction between two unpaired quasineutrons is only weakly dependent upon the configuration and frequency. A comparison of the magnitude of the neutron pairing-correlation parameter obtained from the energy difference between the two-quasineutron Routhians and the sum of the constituent single-quasineutron Routhians with the neutron odd-even mass difference and the pairing-correlation parameter obtained from the E_{0c} of the band crossing in the ^{166}Yb yrast sequence gives a residual interaction of about 300 keV between the unpaired quasineutrons. The dominating portion of the n-n residual interaction is thought to be the "blocking" of the pairing contributions of the unpaired quasineutrons. The experimental alignments of the negative-parity three-quasineutron configurations, $(-,+)_1^3$ and $(-,-)_1^3$, is less than those from either the sum of experimental single-quasineutron alignments or from CSM calculations assuming the Λ_n , which reproduces

the correct frequency of the band crossing in the negative-parity bands. This indicates a further reduction of pairing for the seniority-three states. Although CSM calculations yield correct signature splitting for the negative-parity bands in ^{165}Yb , it fails to account for either the signature splitting in the positive-parity band or the band-crossing frequencies in the positive-parity decay sequences in ^{165}Yb . The source of these discrepancies is not understood, but may be associated with the interactions between the positive-parity quasineutron configurations in the CSM.

The signature dependence of the interband-intraband branching ratios as well as of the interband M1/E2 mixing ratios provides an experimental justification of the signature dependence of the B(M1) transition rates suggested by Hamamoto³³⁾.

We are grateful to Prof. O. C. Kistner for communicating to us the level schemes of $^{167,168}\text{Yb}$ prior to publication. Discussions with Dr. I. Hamamoto and Dr. R. Bengtsson are acknowledged, as is the financial support from the Nordic Committee for Accelerator Based Research and the Danish Natural Science Research Council.

References

- 1) I.Y. Lee, M.M. Aleonard, M.A. Deleplanque, Y. El-Masri, J.O. Newton, R.S. Simon, R.M. Diamond and F.S. Stephens, Phys. Rev. Lett. 38 (1977) 1454
- 2) L.L. Riedinger, W.K. Luk, D.R. Haenni, S.A. Hjorth, N.R. Johnson, I.Y. Lee and R.L. Robinson, in Proc. of the International Conference on Nuclear Physics, Berkeley, Aug. 24-30 (1980) Vol.1, p.383; and L.L. Riedinger, Physica Scripta 24 (1981) 312
- 3) O.C. Kistner, A.W. Sunyar, and E. der Mateosian, Phys. Rev. C17 (1978) 1417; and S.W. Yates, I.Y. Lee, N.R. Johnson, E. Eichler, L.L. Riedinger, M.W. Guidry, A.C. Kahler, D. Cline, R.S. Simon, P.A. Butler, P. Colombani, F.S. Stephens, R.M. Diamond, R.M. Ronningen, R.D. Hichwa, J.H. Hamilton and E.L. Robinson, Phys. Rev. C21 (1980) 2366
- 4) L.L. Riedinger, O. Andersen, S. Frauendorf, J.D. Garrett, J.J. Gaardhøje, G.B. Hagemann, B. Herskind, Y.V. Makovetzky, J.C. Waddington, M. Guttormsen and P.O. Tjøm, Phys. Rev. Lett. 44 (1980) 568; and to be published
- 5) R. Bengtsson and S. Frauendorf, in Proc. Int. Sym. on High-Spin States and Nuclear Structure, Dresden, 1977, p.74; and Aa. Bohr and B.R. Mottelson, Proc. Int. Conf. on Nuclear Structure, Tokyo, Sept. 5-10, 1977, J. Phys. Soc. Japan 44 (1978), suppl. p.157
- 6) R. Bentsson and S. Frauendorf, Nucl. Phys. A327 (1979) 139
- 7) B. Banerjee, H.J. Mang and P. Ring, Nucl. Phys. A215 (1973) 366; A.L. Goodman, Nucl Phys. A230 (1974) 466; P.C. Bhargava and D.J. Thouless, Nucl. Phys. A215 (1973) 515; A. Faessler, K.R. Sandhya Devi, F. Grümmer, K.W. Schmid and R.R. Hilton,

- Nucl. Phys. A256 (1976) 106; and I. Hamamoto, Nucl. Phys. A271 (1976) 15
- 8) L.L. Riedinger, Nucl. Phys. A347 (1980) 141
 - 9) R. Bengtsson, J. de Physique (colloque) C10 (1980) 84
 - 10) S. Frauendorf, in Proc. of the Workshop in Nuclear Physics, Drexel Univ., Sept. 1-3, 1980, ed. D.H. Feng (Plenum Press, New York, 1981)
 - 11) W. Waluś, N. Roy, S. Jónsson, L. Carlén, H. Ryde, G.B. Hagemann, B. Herskind, J.D. Garrett, Y.S. Chen, J. Almerger and G. Leander, Physica Scripta 24 (1981) 324
 - 12) J. Kownacki, J.D. Garrett, G.B. Hagemann, B. Herskind, W. Waluś, N. Roy, S. Jónsson, L. Carlén, H. Ryde, P.J. Twin and P.J. Nolan, Verhandl. DPG (VI) 16 (1981) 728; and to be published
 - 13) O.C. Kistner, C. Baktash, E. der Mateosian, D. Horn, C.J. Lister and A.W. Sunyar, Proc. Int. Conf. on Nuclear Physics, Berkeley, Aug. 24-30 (1980), Vol. 1, p326
 - 14) W. Waluś, N. Roy, S. Jónsson, L. Carlén, H. Ryde, G.B. Hagemann, B. Herskind, J.D. Garrett and J. Kownacki, Verhandl. DPG (VI) 16 (1981) 752
 - 15) J.D. Garrett, O. Andersen, J.J. Gaardhøje, G.B. Hagemann, B. Herskind, J. Kownacki, J.C. Lisle, L.L. Riedinger, W. Waluś, N. Roy, S. Jónsson, H. Ryde, M. Guttormsen and P.O. Tjøm, Phys. Rev. Lett. 47 (1981) 75
 - 16) P.J. Twin, P.J. Nolan, D.M. Todd, P.J. Smith, O. Andersen, J.D. Garrett, G.B. Hagemann and B. Herskind, Verhandl. DPG (VI) 16 (1981) 747; and to be published
 - 17) L.L. Riedinger, G.J. Smith, P.H. Stelson, E. Eichler, G.B. Hagemann, D.C. Hensley, N.R. Johnson, R.L. Robinson and R.O. Sayer, Phys. Rev. Lett. 33 (1974) 1346

- 18) L. Richter, Z. Physik A290 (1979) 213; and L. Richter, H. Backe, E. Kankeleit, F. Weik and R. Willwater, Phys. Lett. 71B (1977) 74
- 19) Th. Lindblad, Nucl. Phys. A238 (1975) 287
- 20) O.C. Kistner et al. (private communication)
- 21) Aa. Bohr and B.R. Mottelson (private communication);
I. Hamamoto, NORDITA preprint 81/28 (to be published)
- 22) M.A.J. Mariscotti, G. Scharff-Goldhaber and B. Buck, Phys. Rev. 178 (1969) 1864
- 23) S.M. Harris, Phys. Rev. 138 (1965) B509
- 24) J.D. Garrett, in Proc. of the XIV Summer School on Nuclear Physics, Mikolajki, Poland, Aug. 31 - Sept. 12, 1981 (to be published in Nukleonika)
- 25) S. Frauendorf, Physica Scripta, 24 (1981) 349
- 26) Aa. Bohr and B.R. Mottelson, Nuclear Structure, Vol. 1 (W.A. Benjamin, Reading, 1969) p.170-171
- 27) J.D. Garrett and S. Frauendorf, NBI preprint 1981
- 28) S.G. Nilsson, C.F. Tsang, A. Sobiczewski, Z. Szymański, S. Wycech, C. Gustafson, I.L. Lamm, P. Möller and B. Nilsson, Nucl. Phys. A131 (1969) 1
- 29) R. Bengtsson and H.-B. Håkansson, Nucl. Phys. A357 (1981) 61
- 30) R. Bengtsson and J.-y. Zhang, to be published in the Proceedings of Nuclear Physics Workshop, Trieste, Oct. 5-10, 1981 ; and R. Bengtsson (private communication)
- 31) R. Bengtsson, I. Hamamoto and B.R. Mottelson, Phys. Lett. 73B (1978) 259
- 32) A. Johnson, H. Ryde and S.A. Hjorth, Nucl. Phys. A179 (1972) 753
- 33) I. Hamamoto, Phys. Lett. 102B (1981) 225; and I. Hamamoto, NORDITA preprint 81/39 (to be published)
- 34) J.J. Gaardhøje, thesis, Univ. of Copenhagen, 1980

Figure Captions

- 1) Examples of γ - γ coincidence spectra from the $^{152}\text{Sm}(^{17}\text{O},4n)^{165}\text{Yb}$ reaction at 80 MeV, obtained with the Compton-suppressed coincidence set-up.
- 2) Examples of γ - γ coincidence spectra from the $^{154}\text{Sm}(^{17}\text{O},4n)^{167}\text{Yb}$ reaction at 80 MeV.
- 3) Level scheme of ^{165}Yb , showing states populated in the $^{152}\text{Sm}(^{17}\text{O},4n)^{165}\text{Yb}$ reaction at 80 MeV.
- 4) Level scheme of ^{167}Yb , showing states populated in the $^{154}\text{Sm}(^{17}\text{O},4n)^{167}\text{Yb}$ reaction at 80 MeV.
- 5) Level scheme of ^{166}Yb , taken from ref.¹¹⁾.
- 6) Routhians and alignments for the ground-state band and the S-band in ^{166}Yb , referred to the g.s.b. reference (shown to the left), and to the yrast reference (shown to the right).
- 7a) Experimental Routhians for various bands in $^{165},^{166},^{167}\text{Yb}$, referred to the ground-state bands and their smooth extrapolations. The moment of inertia parameters used are $\mathcal{J}_1 = 90 \text{ MeV}^{-3} \hbar^4$ and $\mathcal{J}_0 = 27.8, 29.8$ and $31.8 \text{ MeV}^{-1} \hbar^2$ respectively for ^{165}Yb , ^{166}Yb and ^{167}Yb .
- 7b) Experimental alignments for various bands in $^{165},^{166},^{167}\text{Yb}$.
- 8) Nilsson states near the Fermi surface for $^{165},^{166},^{167}\text{Yb}$. The deformation parameters shown at the bottom are from refs.^{9,28)}.
- 9) Construction of 2- and 3-q.p. Routhians using 1-q.p. Routhians.
- 10) Comparison of the experimental and the constructed Routhians for 2- and 3-q.p. bands in $^{165},^{166},^{167}\text{Yb}$.
- 11) Quasineutron spectra in the rotating frame for $^{165},^{167}\text{Yb}$, obtained from CSM calculations and shown

as a function of the rotational frequency $\hbar\omega$. The parameters used, and the parities and signatures of a few trajectories are shown to the right.

- 12) Comparison of the experimental quasineutron spectra for ^{165}Yb , shown as a function of $\hbar\omega$, with those from CSM calculations. The filled circles and the solid lines are the experimental and the theoretical spectra, respectively, for bands with positive signature. Open circles and dashed lines depict the same for bands with negative signature.
- 13) Theoretical and experimental quasineutron spectra for ^{165}Yb and ^{167}Yb , shown as a function of $\hbar\omega$ and referred to the yrast references in ^{166}Yb and ^{168}Yb respectively. The yrast references have been shifted in $\hbar\omega$ so as to make the crossing frequencies of the references coincide with the lowest-frequency crossings in the negative parity bands in $^{165,167}\text{Yb}$.
- 14) $B(M1)$ values for $I \rightarrow I-1$ transitions between states of opposite signature of the $i_{13/2}$ band in $^{165,167}\text{Yb}$. These values were derived using $Q_0 = 7$ eb and the average value of $K \sim 2$. The zigzag line shows the theoretical values³⁴⁾ corresponding to the case where the Fermi surface lies at the $\Omega = 5/2$ level of the $i_{13/2}$ states.

Table 1.

The energies , intensities and angular distribution coefficients for the transitions assigned to ^{165}Yb following the $^{152}\text{Sm}(^{17}\text{O},4n)^{165}\text{Yb}$ reaction at 80 MeV .

E_γ ^{a)} (keV)	Rel. Int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	$I_i^\pi \rightarrow$	I_f^π
39.2				$9/2^+$	$7/2^-$
83.0				$11/2^+$	$9/2^+$
87.5				$7/2^-$	$5/2^-$
90.2				$13/2^+$	$9/2^+$
110.0				$9/2^-$	$7/2^-$
197.4	168	0.24(03)	-0.03(03)	$9/2^-$	$5/2^-$
202.1	147	-0.88(03)	0.14(03)	$15/2^+$	$13/2^+$
206.0	1080	0.27(01)	-0.04(01)	$17/2^+$	$13/2^+$
209.5	269	0.23(04)	-0.08(04)	$15/2^+$	$11/2^+$
274.6	14 ^{d)}			$13/2^-$	$11/2^+$
287.0	178	0.34(05)	-0.18(06)	$13/2^-$	$9/2^-$
322.2	1000	0.33(01)	-0.09(01)	$21/2^+$	$17/2^+$
335.2	75	-0.81(06)	0.23(07)	$19/2^+$	$17/2^+$
336.1	weak			$33/2^-$	$31/2^+$
339.1	310	0.31(02)	-0.07(02)	$19/2^+$	$15/2^+$
365.6	177	0.35(02)	-0.12(03)	$17/2^-$	$13/2^-$
429.1	851	0.34(02)	-0.08(02)	$25/2^+$	$21/2^+$
430.6	190 ^{d)}	0.33(03)	-0.11(03)	$21/2^-$	$17/2^-$
431	weak			$17/2^-$	$15/2^+$
453.2	338	0.35(03)	-0.11(03)	$23/2^+$	$19/2^+$
466.1	80	-0.38(10)	0.12(10)	$23/2^+$	$21/2^+$
469.1	38	0.22(10)	0.13(10)	$31/2^-$	$27/2^-$

Table 1.
(cont'd.)

$E_\gamma^a)$ (keV)	Rel. Int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	$I_i^\pi \rightarrow I_f^\pi$	
477.7 } 477.7 }	341	0.33(07)	-0.07(07)	25/2 ⁻	21/2 ⁻
				33/2 ⁻	29/2 ⁻
488	85 ^{d)}			29/2 ⁻	27/2 ⁺
490.1	110 ^{d)}	0.29(02)	-0.08(02)	29/2 ⁻	25/2 ⁻
506.0	121	0.24(06)	-0.13(06)	35/2 ⁻	31/2 ⁻
516.9	116	0.41(05)	-0.05(05)	37/2 ⁻	33/2 ⁻
522	30 ^{d)}			21/2 ⁻	19/2 ⁺
523.6	644	0.31(05)	-0.06(05)	29/2 ⁺	25/2 ⁺
541.5	19	-0.46(36)	-0.13(40)	39/2 ⁻	37/2 ⁺
546.8	42	-0.39(14)	-0.10(14)	25/2 ⁻	23/2 ⁺
549.4	219	0.32(05)	-0.06(05)	27/2 ⁺	23/2 ⁺
566.0	84	0.34(06)	-0.12(06)	39/2 ⁻	35/2 ⁻
580.8	106	0.32(04)	0.01(04)	41/2 ⁻	37/2 ⁻
586.3	54	-0.12(12)	0.00(13)	27/2 ⁺	25/2 ⁺
605.5	398	0.28(03)	-0.05(03)	33/2 ⁺	29/2 ⁺
627.6	74	0.38(10)	0.10(12)	unassigned	
629.1	141	0.19(06)	0.02(06)	31/2 ⁺	27/2 ⁺
635.4	39	0.21(10)	0.00(10)	43/2 ⁻	39/2 ⁻
648.8	48	0.40(14)	0.00(14)	45/2 ⁻	41/2 ⁻
650.4	75	-0.23(05)	-0.05(06)	35/2 ⁻	33/2 ⁺
674.8	199	0.25(04)	-0.07(04)	37/2 ⁺	33/2 ⁺
695.1	53	0.14(10)	0.07(10)	35/2 ⁺	31/2 ⁺
704	26				23/2 ⁺
706.0	36	0.24(10)	-0.02(10)	47/2 ⁻	43/2 ⁺
715.8	20	0.44(28)	0.01(28)	49/2 ⁻	45/2 ⁻

Table 1.
(cont'd.)

E_γ ^{a)} (keV)	Rel. Int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	$I_i^\pi \rightarrow$	I_f^π
728.1 } 728.1	108	0.15(06)	-0.11(06)	41/2 ⁺ 45/2 ⁺	37/2 ⁺ 41/2 ⁺
733	14 ^{d)}			(49/2 ⁺)	45/2 ⁺
749.1	36	0.38(29)	-0.51(29)	39/2 ⁺	35/2 ⁺
750.1	63	-0.42(19)	0.43(22)	31/2 ⁻	29/2 ⁺
771	weak				21/2 ⁺
775	weak			51/2 ⁻	47/2 ⁻
780	22	0.74(30)	-0.34(20)	53/2 ⁻	49/2 ⁻
804.6	51	-0.47(13)	0.32(14)	27/2 ⁻	25/2 ⁺

a) The energies are accurate to within 0.2 keV for strong lines (rel. int. ≥ 100). For weaker lines, the error may rise to 0.5 keV.

b) Estimated errors are less than 10% for strong lines.
For weak lines errors may rise to 20% .

c) Only fitting errors are given.

d) From coincidence data, not corrected for possible angular correlation effects.

Table 2.

The energies, intensities and angular distribution coefficients for the transition assigned to ^{167}Yb following the $^{154}\text{Sm}(^{18}\text{O}, 5n)^{167}\text{Yb}$ reaction at 84 MeV.

$E_\gamma^{\text{a)}}$ (keV)	Rel. Int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	$I_i^\pi \rightarrow I_f^\pi$	
29.6 ^{d)}				$5/2^+$	$5/2^-$
33.8 ^{d)}				$7/2^+$	$5/2^-$
60.1	360 ^{e)}			$13/2^+$	$11/2^+$
61.1				$25/2^+$	$23/2^+$
67.4				$11/2^+$	$9/2^+$
76.9				$21/2^+$	$19/2^+$
77.7	150 ^{f)}			$17/2^+$	$15/2^+$
78.6				$7/2^+$	$5/2^-$
91.9				$11/2^+$	$7/2^+$
100.1				$9/2^-$	$7/2^-$
120.2	55	-0.04(17)	-0.00(12)	$9/2^-$	$9/2^+$
127.5	413	-0.23(03)	-0.06(03)	$13/2^+$	$9/2^+$
144.2	458	-0.73(03)	0.14(07)	$15/2^+$	$13/2^+$
144.9	80 ^{f)}			$9/2^-$	$7/2^+$
178.7	78	0.09(06)	-0.01(07)	$9/2^-$	$5/2^-$
204.4	760	0.27(03)	-0.05(04)	$15/2^+$	$11/2^+$
221.9	1000	0.28(03)	-0.06(04)	$17/2^+$	$13/2^+$
236.5	286	-0.72(03)	-0.01(03)	$19/2^+$	$17/2^+$
263.5	152	0.21(02)	-0.03(02)	$13/2^-$	$9/2^-$
313.5	1760	0.47(16)	-0.18(16)	$21/2^+$	$17/2^+$
314.2	533	0.23(11)	-0.13(12)	$19/2^+$	$15/2^+$
316.6	147 ^{g)}	0.41(05)	0.10(05)	$13/2^-$	$11/2^+$
339.4	130	-0.65(03)	-0.08(04)	$23/2^+$	$21/2^+$

Table 2.

(cont'd)

$E_\gamma^{a)}$ (keV)	Rel. Int. $b)$	Ang. dist. coeff. $c)$		Assignments	
		A_2/A_0	A_4/A_0	I_i^π	$\rightarrow I_f^\pi$
341.2	232	0.26(02)	-0.09(02)	$17/2^-$	$13/2^-$
400.5	1515	0.28(04)	-0.07(05)	$25/2^+$	$21/2^+$
409.1	330	0.33(03)	-0.06(03)	$21/2^-$	$17/2^-$
416.4	616	0.24(03)	-0.04(03)	$23/2^+$	$19/2^+$
447.8	73	-0.52(05)	0.13(06)	$27/2^+$	$25/2^+$
453	120 $f)$			$17/2^-$	$15/2^+$
463.9	343	0.25(03)	-0.03(04)	$25/2^-$	$21/2^-$
479.4	1275	0.26(04)	-0.06(04)	$29/2^+$	$25/2^+$
501.8	331	0.22(02)	-0.10(03)	$29/2^-$	$25/2^-$
508.9	660	0.20(03)	-0.05(04)	$27/2^+$	$23/2^+$
525	weak			$33/2^-$	$31/2^+$
525.3	344	0.18(03)	-0.07(03)	$33/2^-$	$29/2^-$
547.0	1030	0.26(05)	-0.08(05)	$33/2^+$	$29/2^+$
548	40 $f)$			$21/2^-$	$19/2^+$
553	524 $g)$	0.48(07)	-0.19(07)	$37/2^-$	$33/2^-$
557.4	weak			$31/2^+$	$29/2^+$
588.9	425 $g)$	0.17(02)	-0.02(02)	$31/2^+$	$27/2^+$
589	weak			$29/2^-$	$27/2^+$
596	weak			$25/2^-$	$23/2^+$
600	227	0.22(06)	-0.07(07)	$41/2^-$	$37/2^-$
602.8	775 $g)$	0.19(02)	-0.05(03)	$37/2^+$	$33/2^+$
647.6	340 $g)$	0.08(02)	0.06(03)	$41/2^+$	$37/2^+$
658	240	0.13(04)	0.06(05)	$35/2^+$	$31/2^+$
660	weak			$45/2^-$	$41/2^-$

Table 2.

(cont'd.)

E_γ ^{a)} (keV)	Rel. Int. ^{b)}	Ang. dist. coeff. ^{c)}		Assignments	
		A_2/A_0	A_4/A_0	I_i^π	$\rightarrow I_f^\pi$
692.3	bad background			45/2 ⁺	41/2 ⁺
715	weak			39/2 ⁺	35/2 ⁺
716	weak			49/2 ⁻	45/2 ⁻
742	weak			49/2 ⁺	45/2 ⁺
760	weak			43/2 ⁺	39/2 ⁺
801	weak			53/2 ⁺	49/2 ⁺

-
- a) Estimated errors are less than 0.2 keV for the strong lines (rel. int. ≥ 200), rising to 0.5 for weaker lines.
- b) Estimated errors are less than 10% for strong lines. For weak lines it may rise to 20%.
- c) Only fitting errors are given.
- d) From the work of Th. Lindblad (ref 18.).
- e) From intensity balance of the transitions feeding and depopulating the 13/2⁺ level.
- f) From coincidence data, not corrected for possible angular correlation effects.
- g) Not corrected for the contribution from contaminant lines.

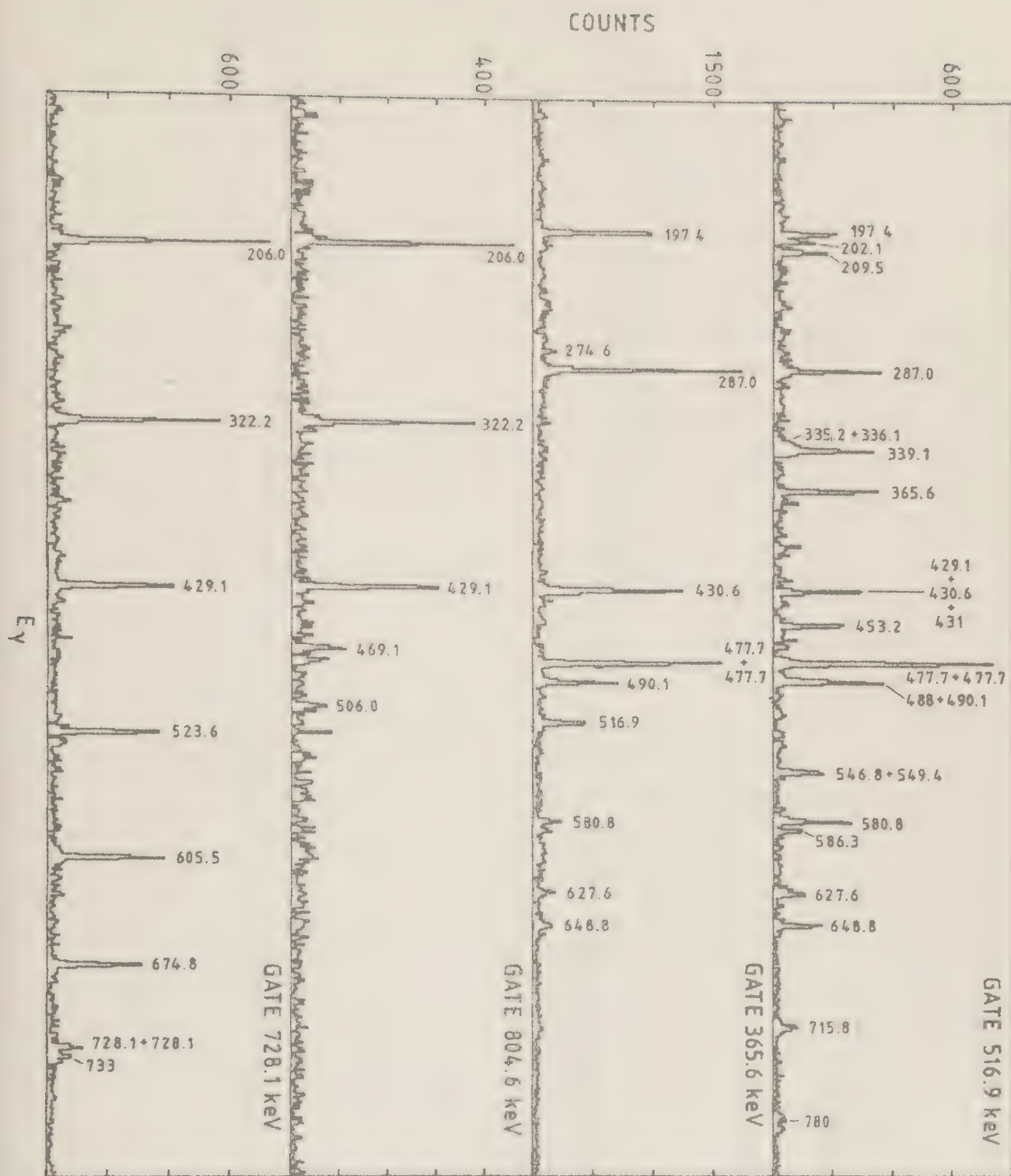


Fig. 1.

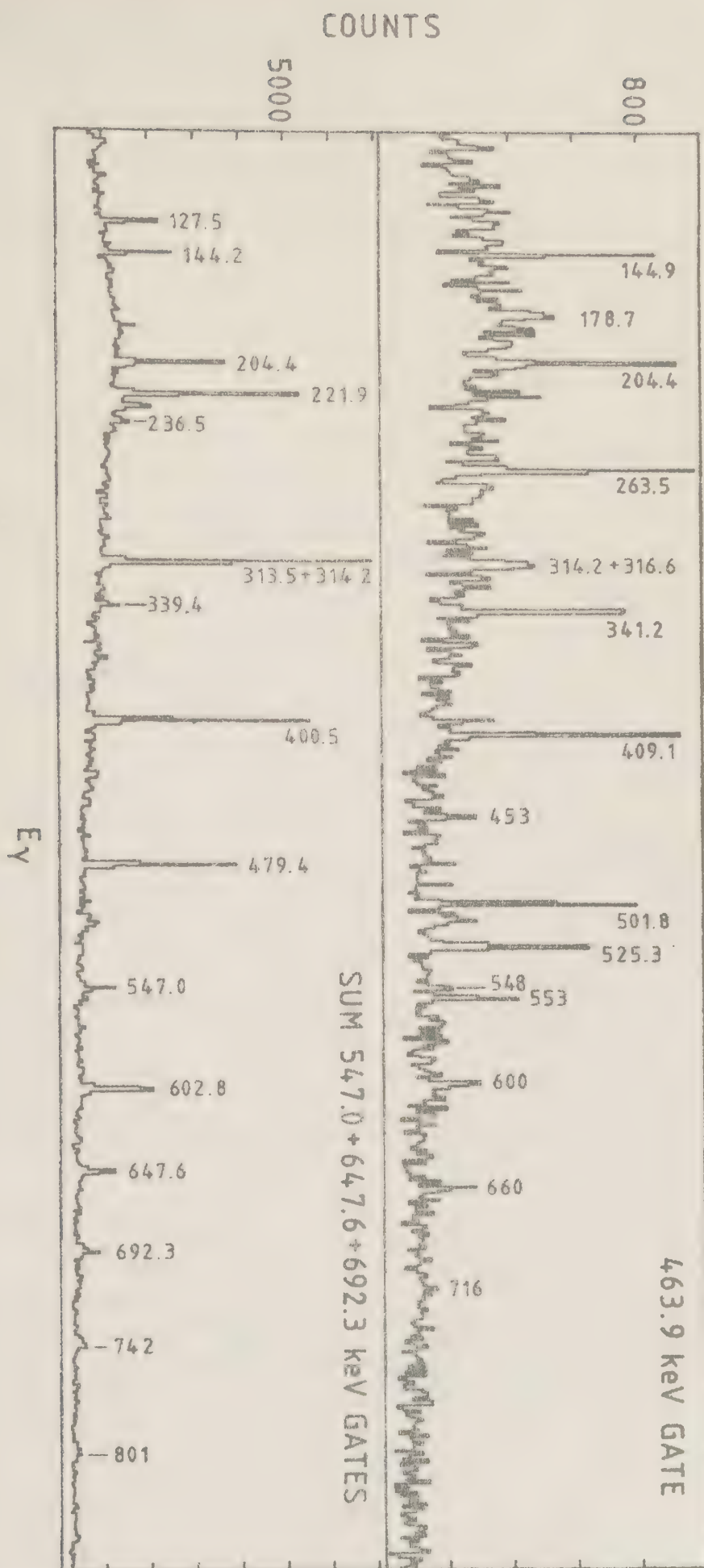


Fig. 2.

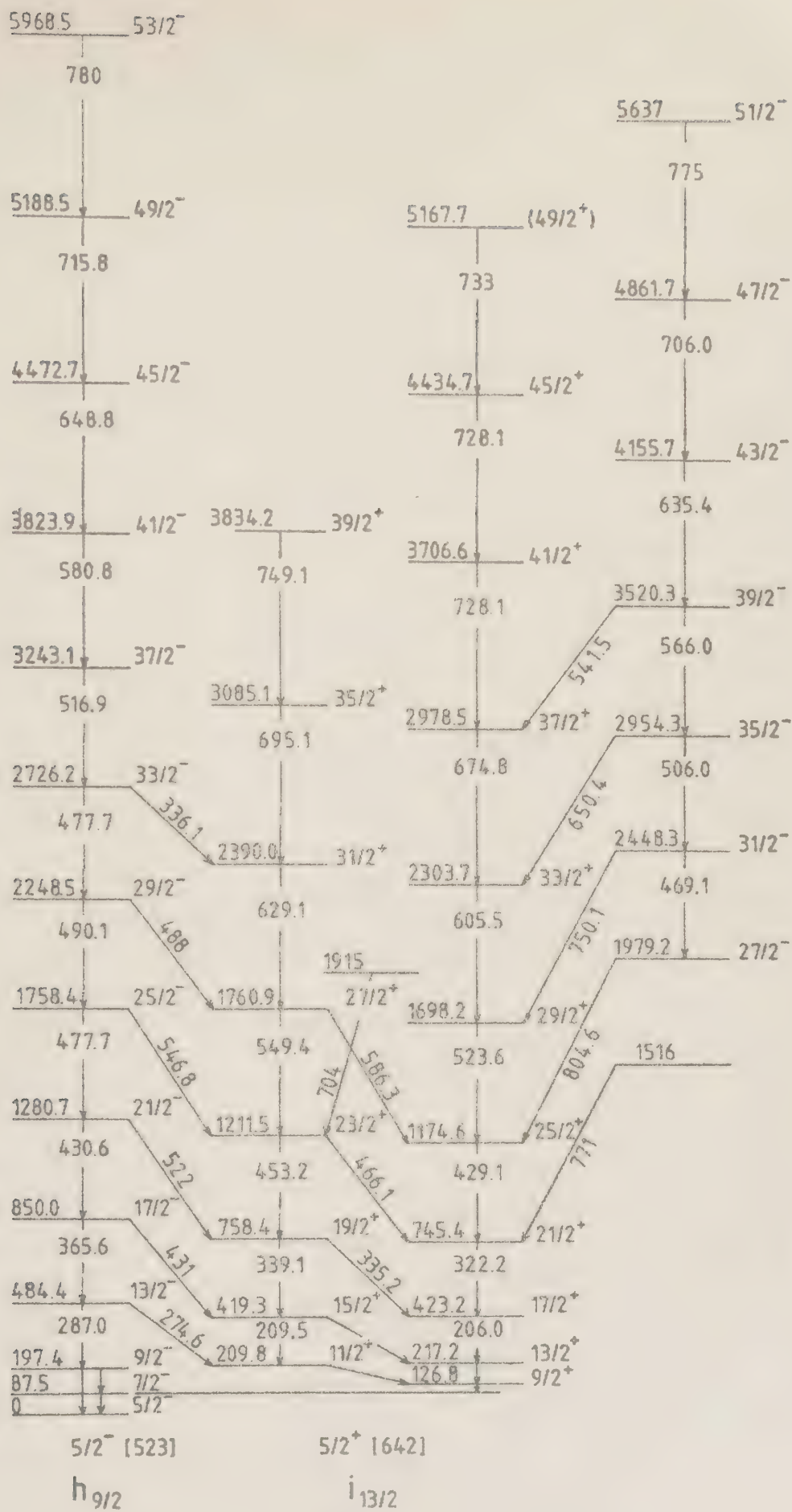


Fig. 3.

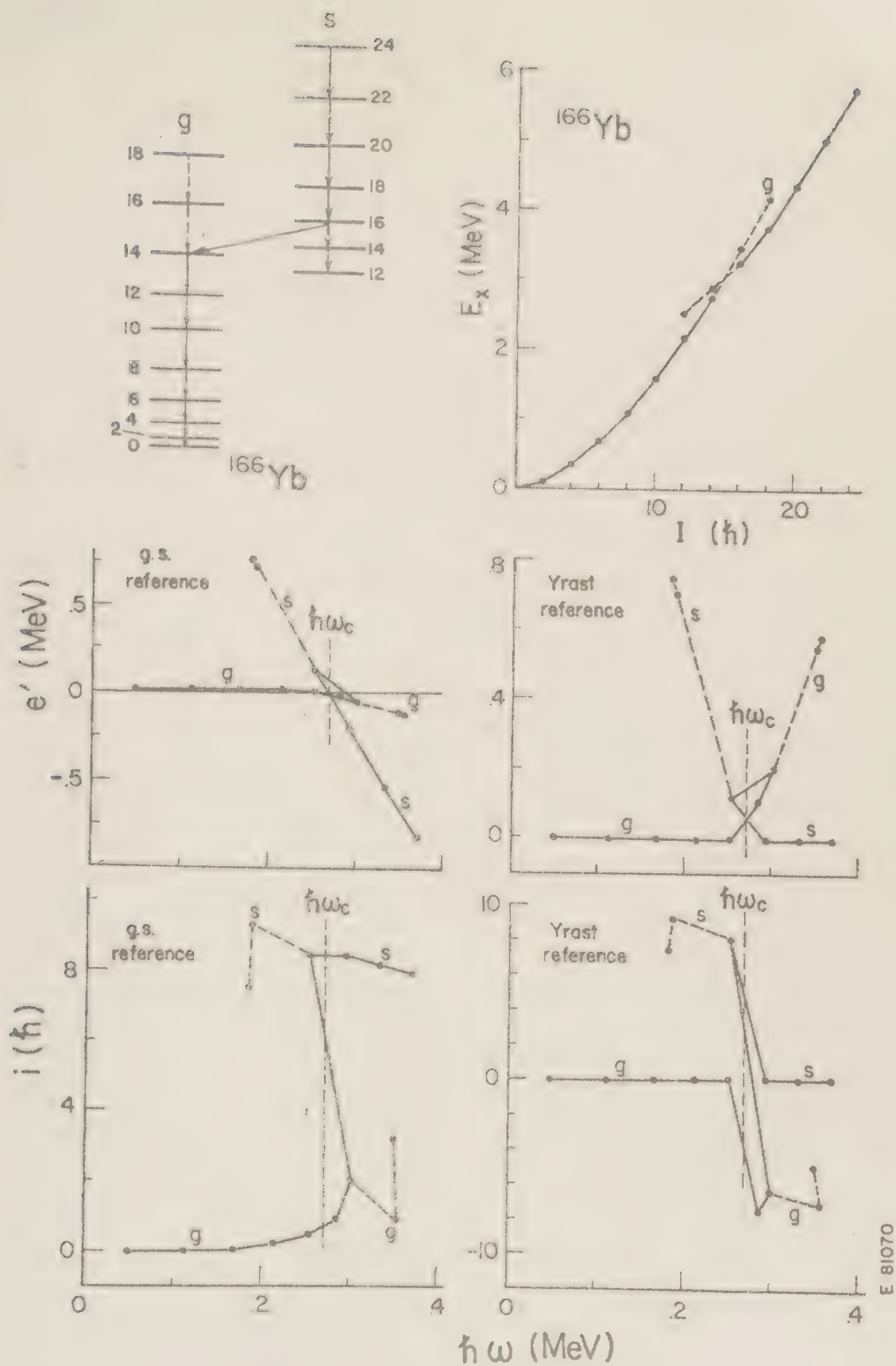


Fig. 6.

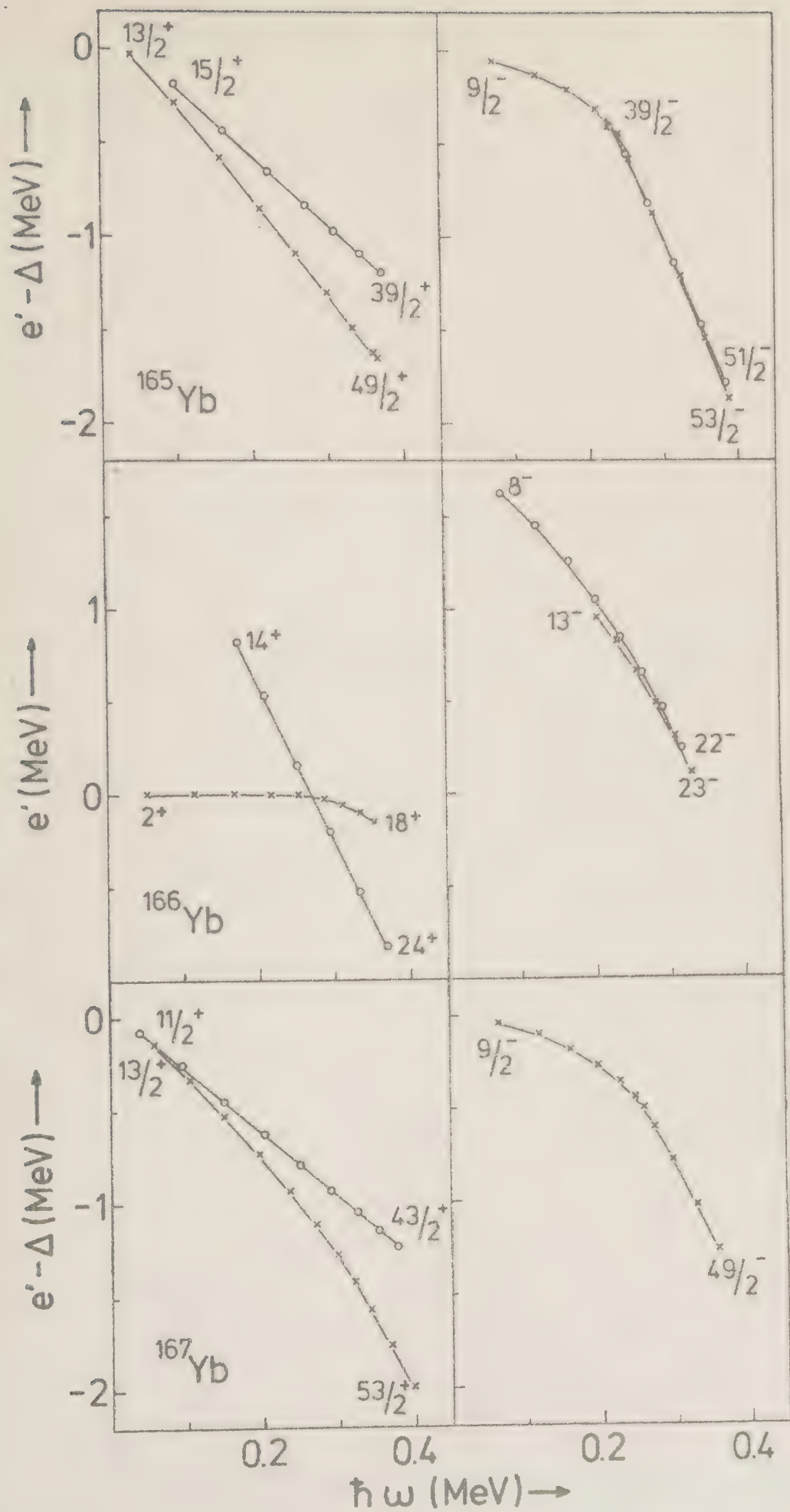


Fig. 7a.

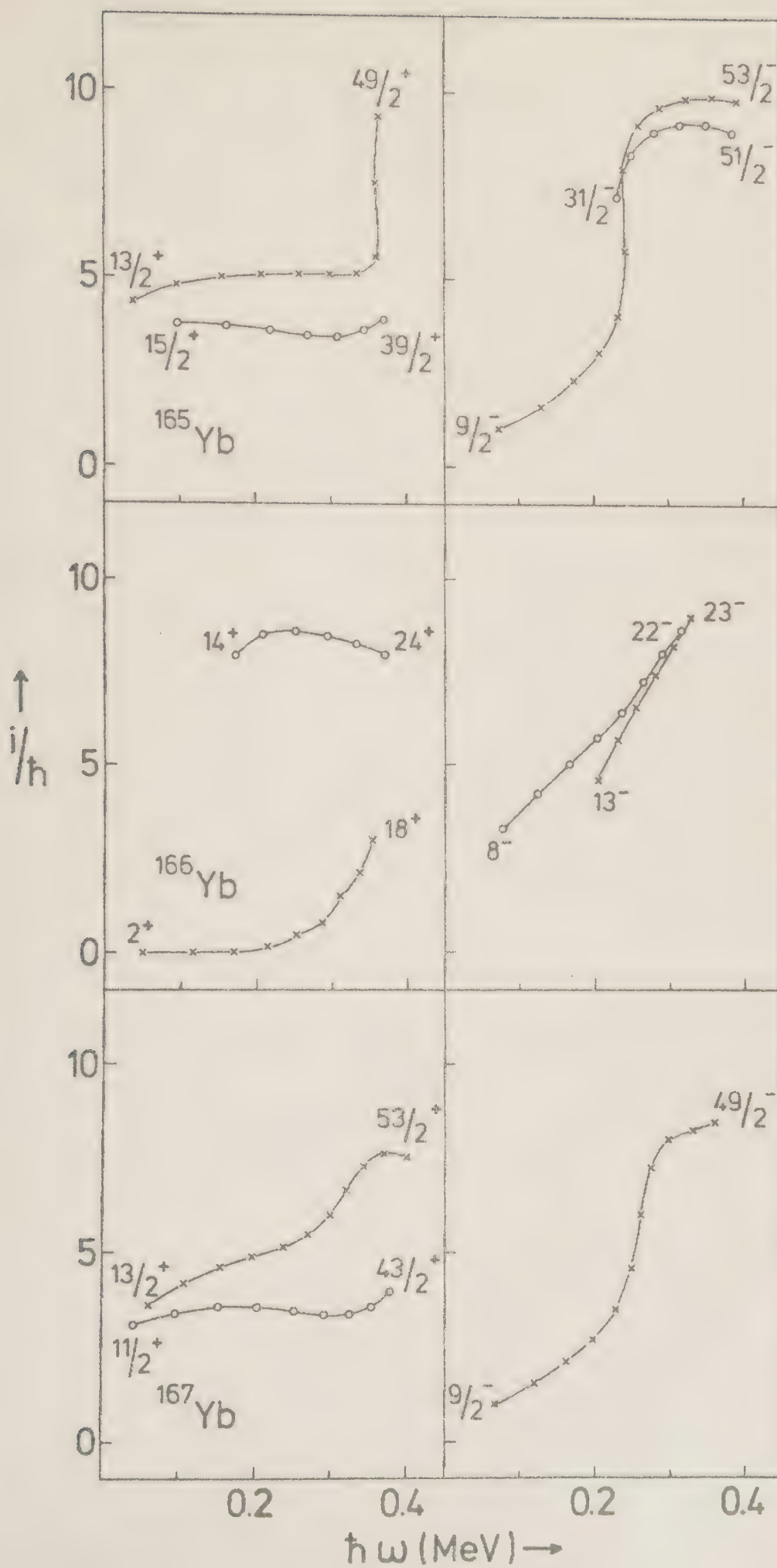


Fig. 7b.

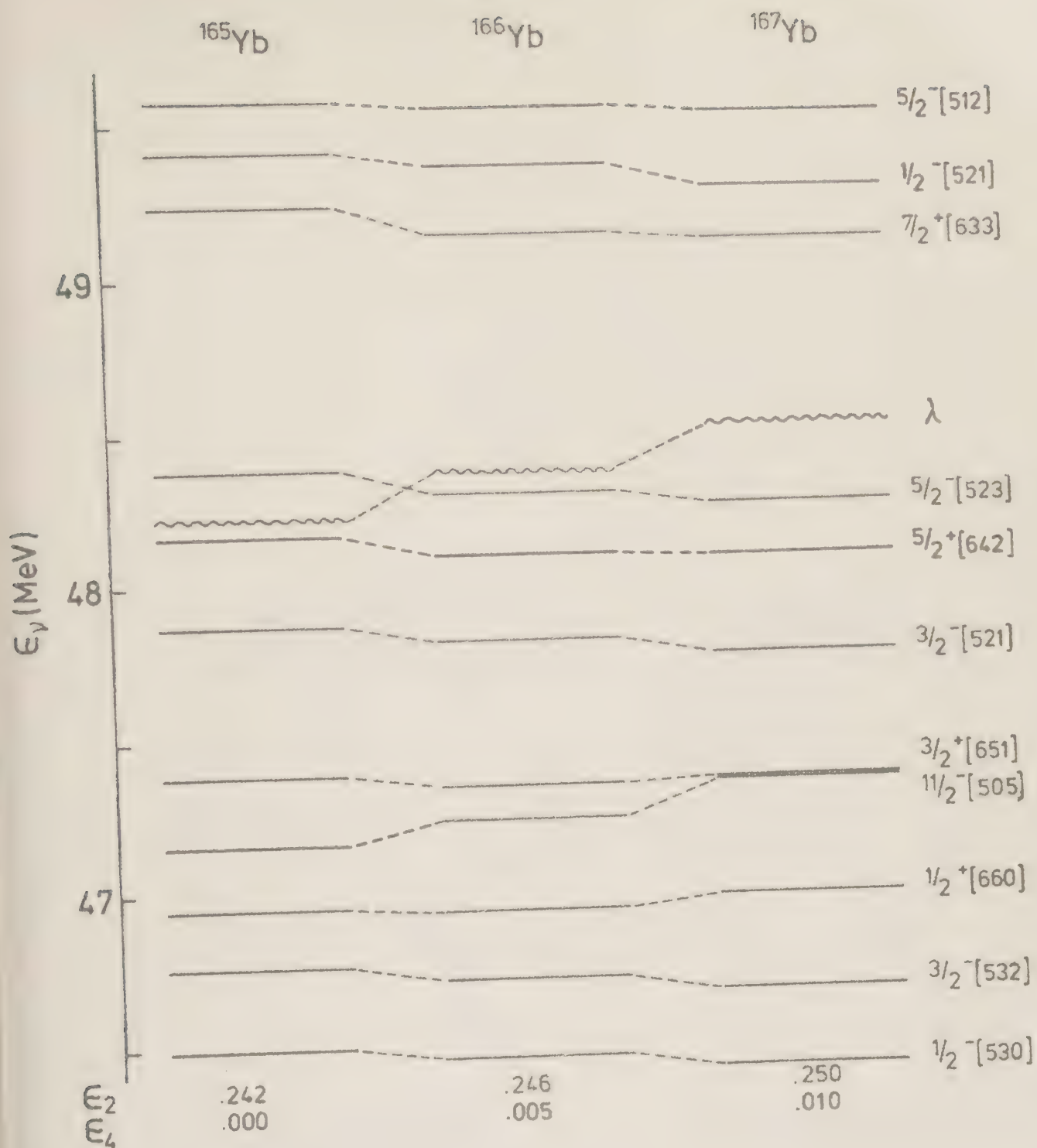


Fig. 8.

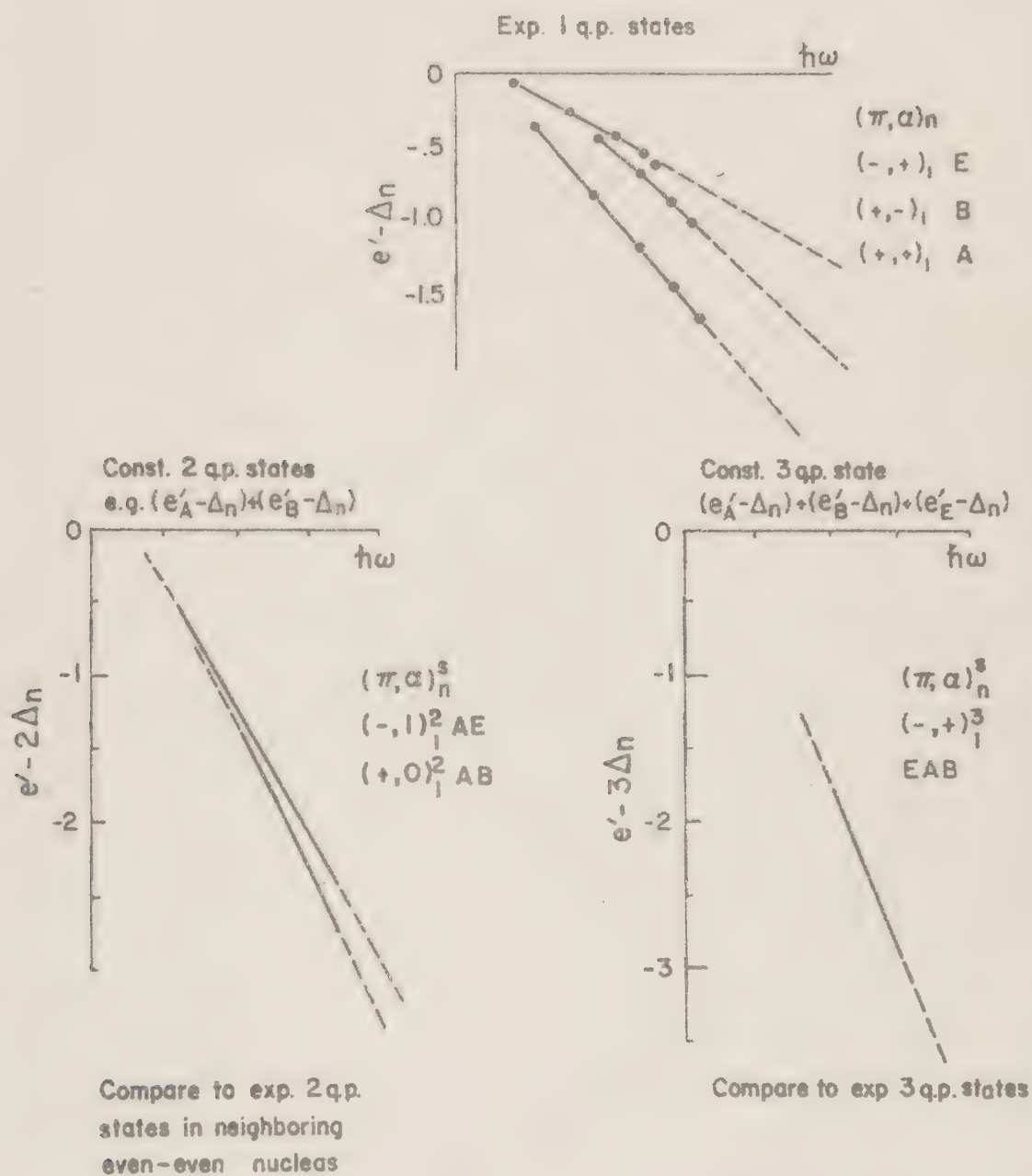


Fig. 9.

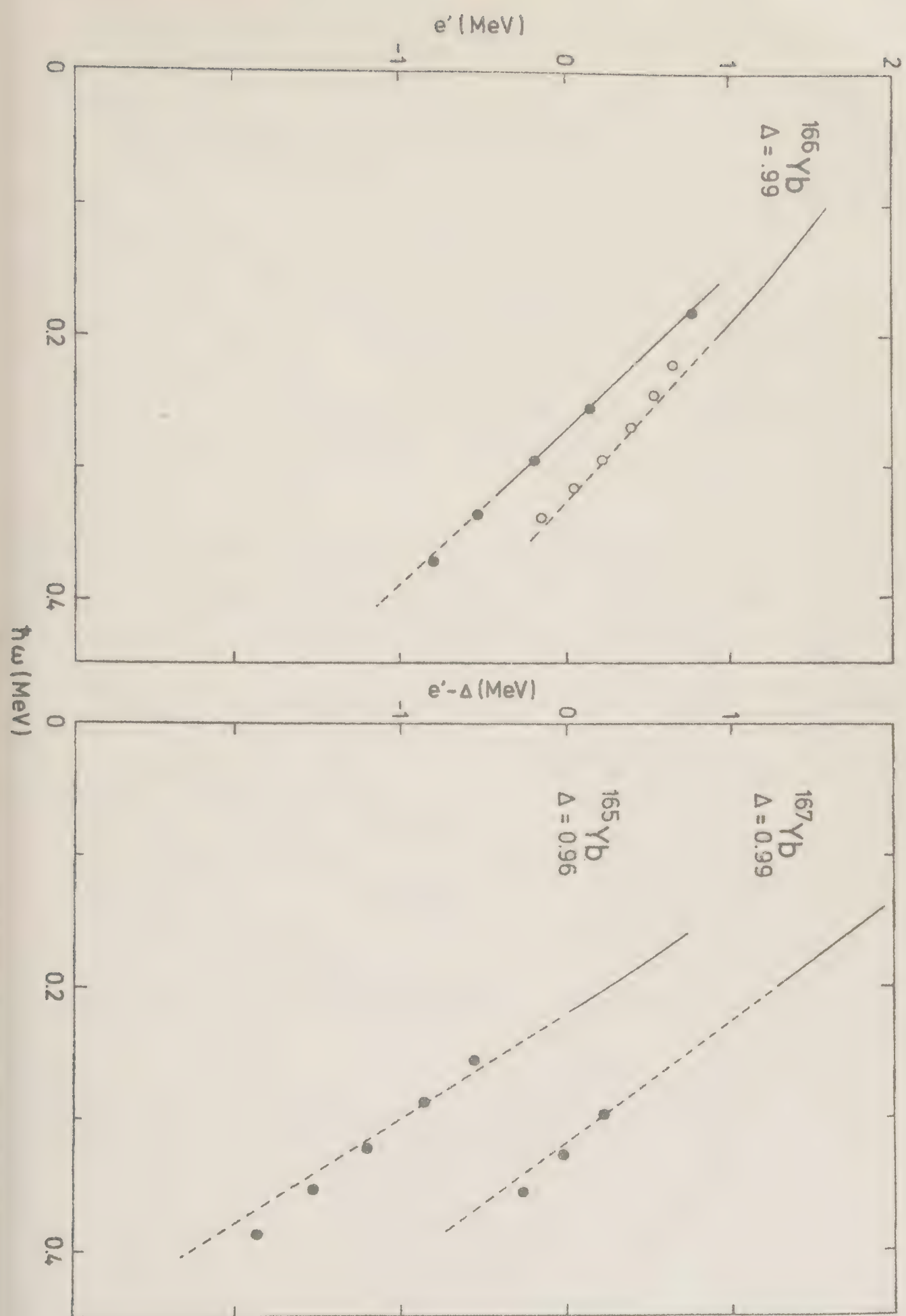


Fig. 10.

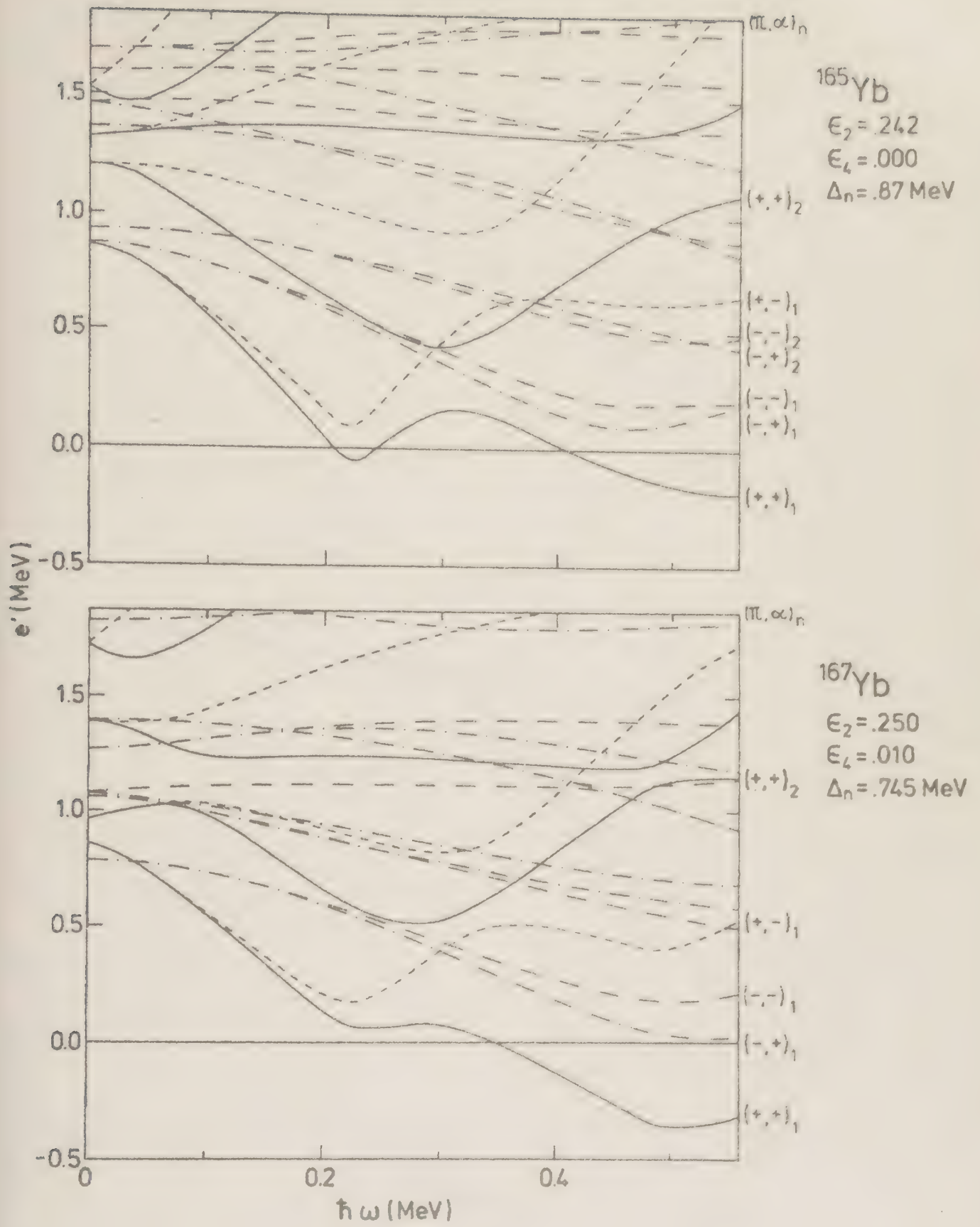


Fig. 11.

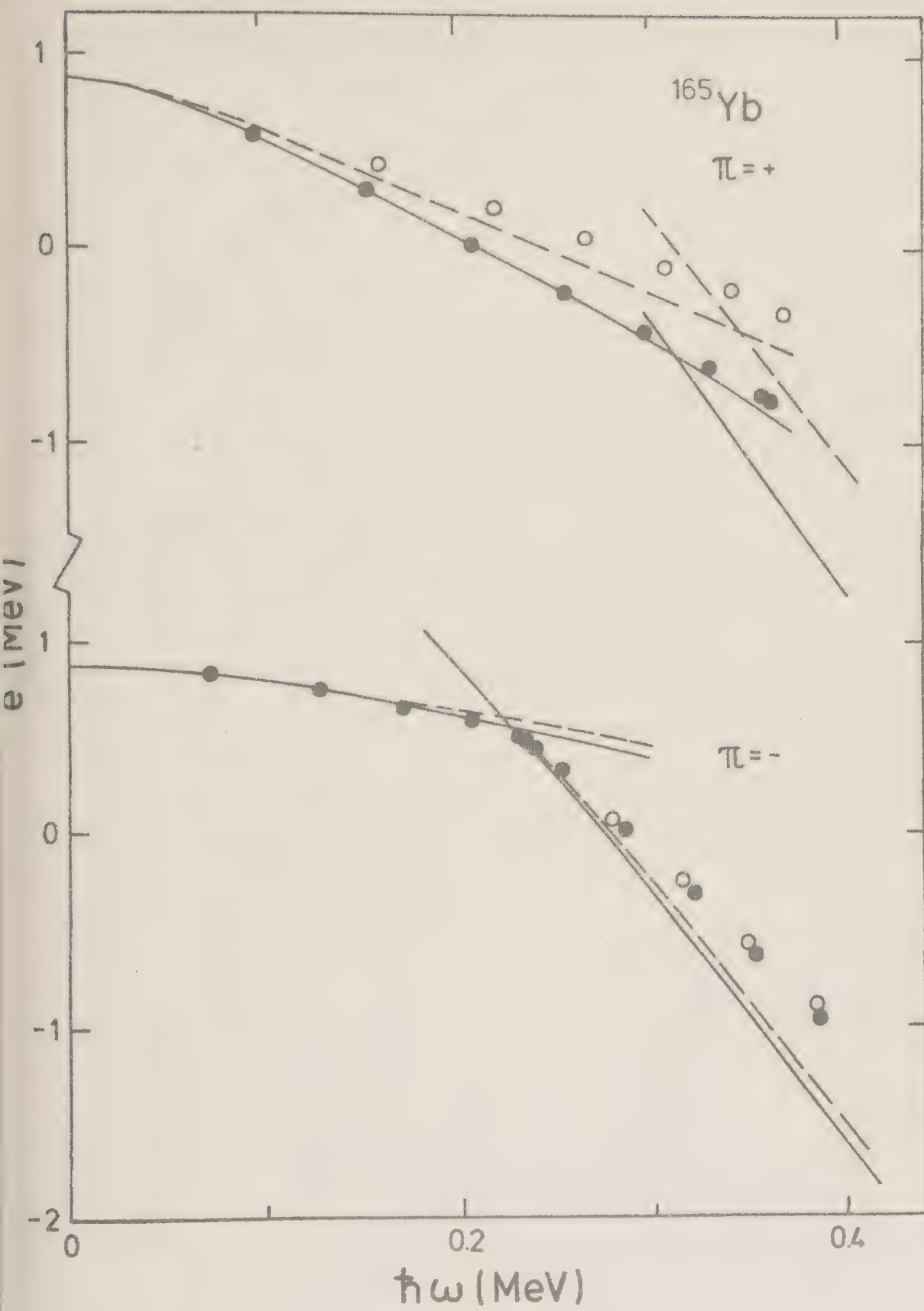


Fig. 12.

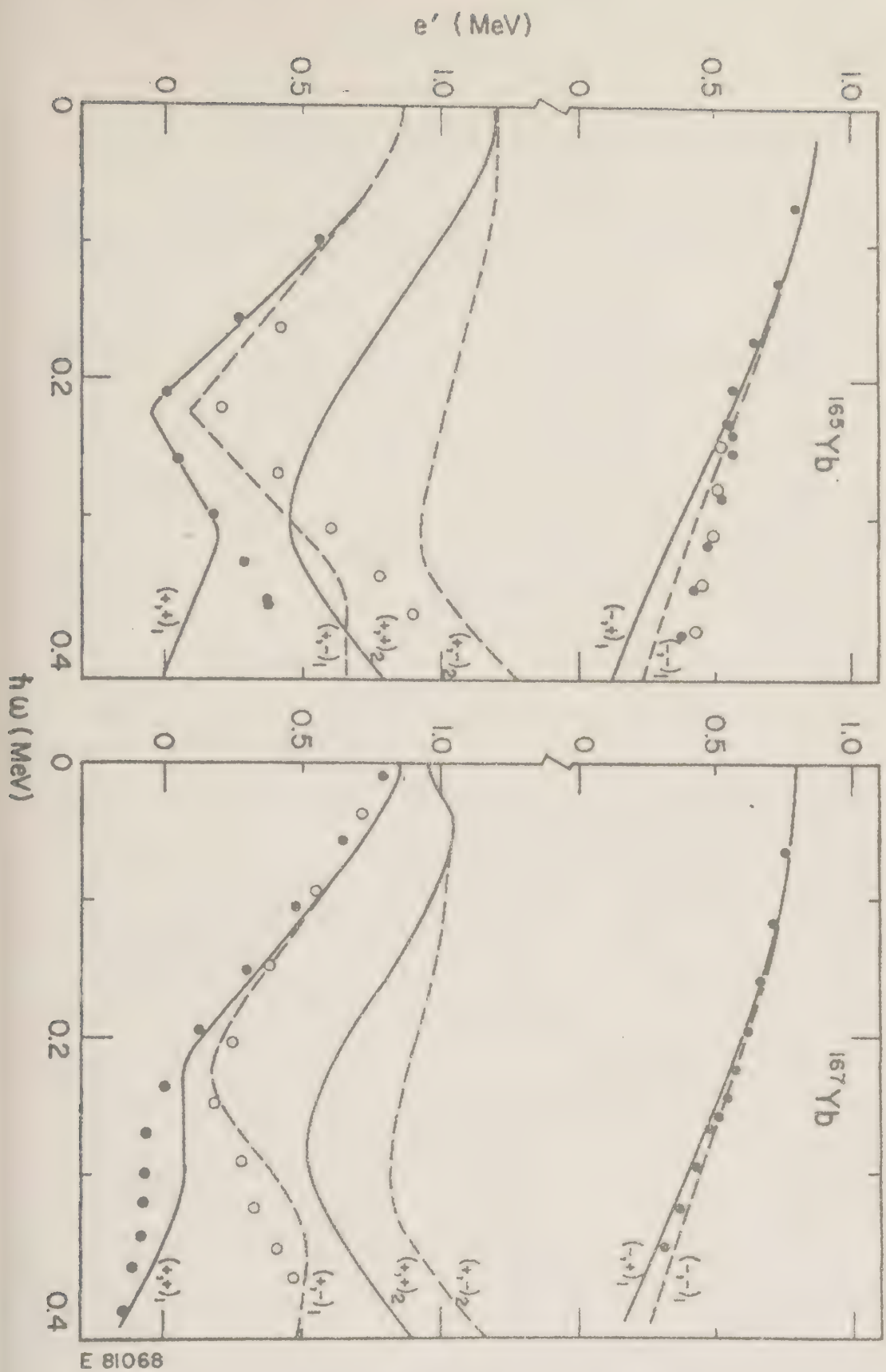


Fig. 13.

$B(M1: I \rightarrow I-1) \text{ in } (e\hbar/2mc)^2$

0.1

0.2

0.3

$13/2$

$17/2$

$21/2$

$25/2$

$29/2$

I

x

o

^{165}Yb

^{167}Yb

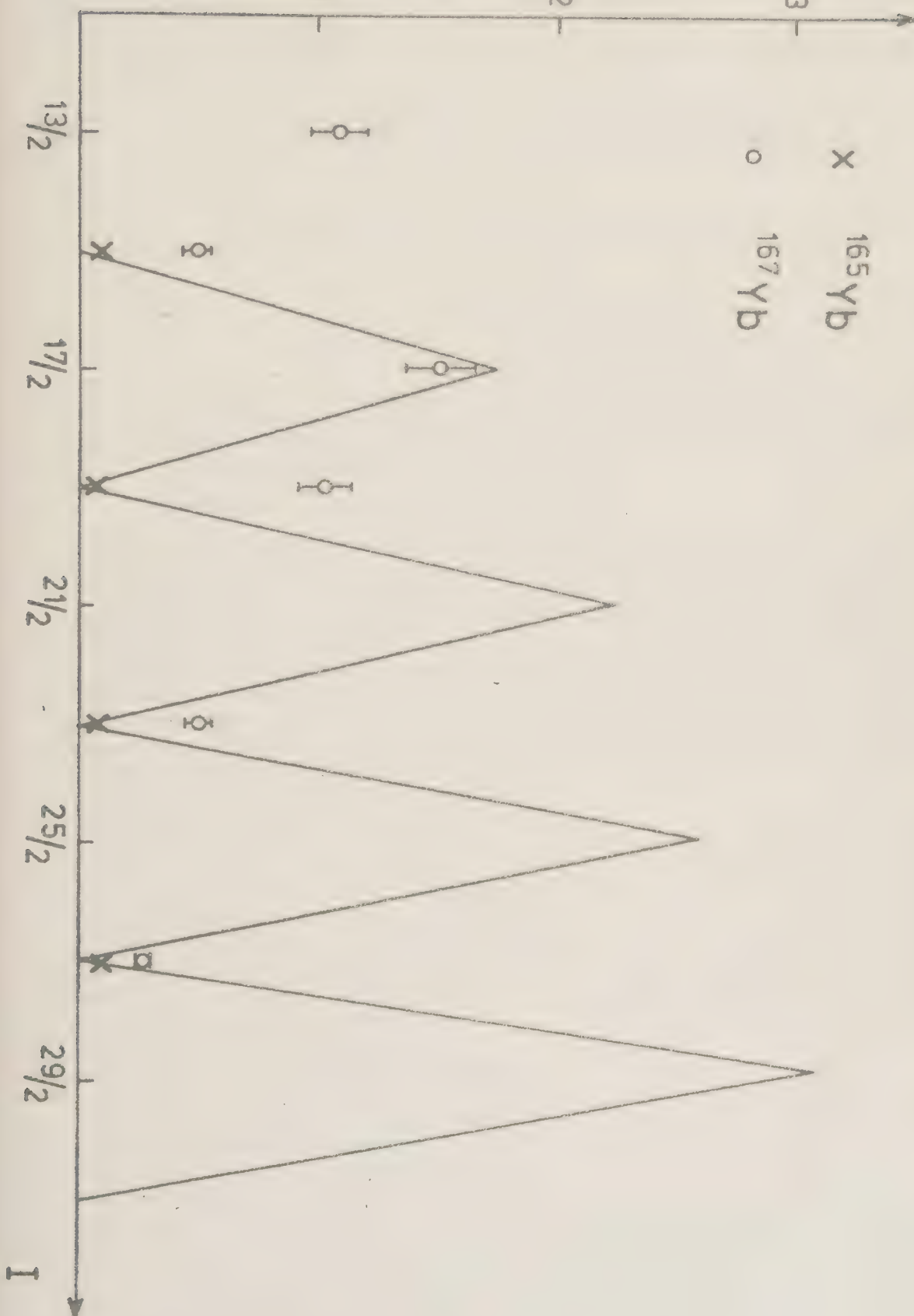


Fig. 14.

Evidence for Decreased Pairing Energies in Odd- N Nuclei from Band-Crossing Frequencies

J. D. Garrett, O. Andersen, J. J. Gaardhøje, G. B. Hagemann, B. Herskind,
J. Kownacki,^(a) J. C. Lisle,^(b) and L. L. Riedinger^(c)
The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark

and

W. Walús,^(d) N. Roy, S. Jönsson, and H. Ryde
Department of Physics, University of Lund, S-223 Lund, Sweden

and

M. Guttormsen and P. O. Tjøm
Institute of Physics, University of Oslo, N-1000 Oslo, Norway
(Received 23 March 1981)

An odd-even neutron-number dependence of the alignment frequency of the first pair of $i_{13/2}$ quasineutrons in rare-earth nuclei is established. This effect is explained by a reduction of the neutron pairing-correlation parameter Δ_n for odd- N systems as compared to seniority-zero configurations in even- N nuclei.

PACS numbers: 21.10.Re, 27.70.+q

The cranked shell model has been successful in reproducing many of the spectroscopic properties of the near-yrast region of deformed nuclei up to $I \approx 30$ assuming a constant, large pairing-correlation parameter, Δ .¹⁻³ It is expected, however, that pairing should decrease with increasing angular momentum. The present Letter addresses this problem. Experimental evidence is reported for an odd-even neutron-number dependence of the angular frequency at which it is energetically more favorable for the first pair of $i_{13/2}$ neutrons to be aligned. Such a behavior can be explained by a reduction of the neutron pairing-correlation parameter, Δ_n , for the odd- N system as compared to the seniority-zero neutron configurations in even- N nuclei. The reduction in Δ_n presumably is the result of the "blocking" of the pairing contribution from a quasineutron orbit near the Fermi surface, and therefore is expected to be a function of the number of unpaired neutrons.

To establish the angular frequency, $\hbar\omega$, at which it is energetically favorable for a quasineutron pair to be aligned, it is convenient to express the information contained in the level schemes in terms of $\hbar\omega$ and the experimental excitation energy in a rotating frame,^{1,2} e' , or the Routhian. Nonrotational features, interpreted as band crossings, are apparent from the variation of e' as a function of $\hbar\omega$ for a specific cascade—see Fig. 1. The band-crossing frequencies, $\hbar\omega_c$, are well defined in such a plot. In even-even rare-earth nuclei the lowest-frequency band crossing corresponds to the crossing of the ground-state band

with the aligned two-quasineutron "S band." This band crossing, which corresponds to the alignment of a pair of $i_{13/2}$ quasineutrons,⁴ is responsible for the "backbends" observed in the yrast sequence of even-even rare-earth nuclei. A band crossing corresponding to the alignment of the same two quasineutrons can be observed in the low-lying negative-parity bands of the odd- N nuclei.² Here a band based on negative-parity, sin-

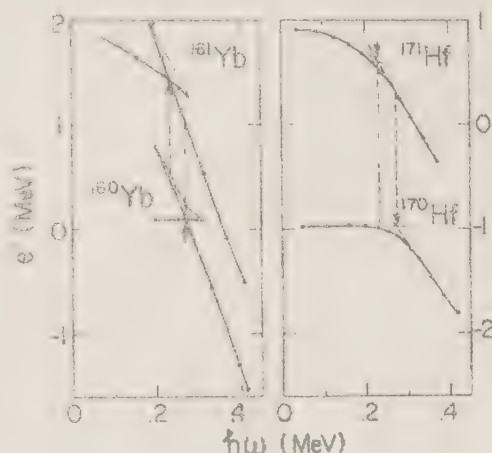


FIG. 1. Experimental Routhian, e' , as a function of $\hbar\omega$ for the yrast bands of ^{160}Yb and ^{170}Hf and the lowest negative-parity bands of ^{161}Yb and ^{171}Hf indicating the definition of $\hbar\omega_c$ for weakly interacting bands ($^{160}, ^{161}\text{Yb}$) and strongly interacting bands ($^{170}, ^{171}\text{Hf}$). The ordinate scale on the left- and right-hand sides applies to even- and odd-mass nuclei, respectively.

gle quasineutrons crosses a three-quasineutron band involving the unpaired, negative-parity quasineutron as well as the same two $i_{13/2}$ quasineutrons, which are the configuration of the S band in the even-even nuclei.

Experimental band crossing (or alignment) frequencies have been obtained for a large number of Er,⁵ Yb,^{3,6} Hf,⁷ and W⁸ nuclei. The systematic behavior of $\hbar\omega_c$ is shown as a function of neutron number in Fig. 2. Throughout the $N=90-102$ mass region the $\hbar\omega_c$ corresponding to the alignment of the first pair of quasineutrons is systematically lower for odd- N nuclei than for even-even nuclei. This systematic variation of $\hbar\omega_c$ between odd- and even- N nuclei is not a result of the technique of defining $\hbar\omega_c$ from the experimental Routhians. The crossing frequencies are nearly independent of the Harris parameters² used to remove the excitation energy of the rotating core. If a nonzero value of K is assumed for the S band, the magnitude of the odd-even variation of $\hbar\omega_c$

would be even larger.

For odd- Z rare-earth nuclei the level schemes are not established sufficiently high in $\hbar\omega$ to define the crossing frequency from experimental Routhians. Some information, however, is available⁹ for ^{169}Lu . For this $N=98$ nucleus the slope of e' changes sufficiently slowly with $\hbar\omega$ so that it is possible to obtain information on $\hbar\omega_c$ from the plot of the alignment ($i \equiv -de'/d\omega$) as a function of $\hbar\omega$. For the $[541] \frac{1}{2}$ proton band in $^{169}\text{Lu}_{98}$ the $di/d\omega$ for given $\hbar\omega$ in the "crossing region" is nearly identical to that of its isotone $^{170}\text{Hf}_{98}$ and is quite different from that for the neighboring odd- N system $^{171}\text{Hf}_{99}$; see Fig. 3. A similar conclusion can be made from a comparison of i vs $\hbar\omega$ for bands in $^{165}\text{Tm}_{10}$ with that of the appropriate bands in the neighboring even-even and odd- N nuclei.

The angular frequency of the alignment of the first pair of neutrons is less for odd- N nuclei than for even- N nuclei. These alignment or band-crossing frequencies, however, are nearly constant for isotones and for a number of even-even rare-earth nuclei of different Z , N , and deformations. Cranked shell model (CSM) calculations (see Fig. 4) indicate that such systematics may be explained by a reduction of the neutron pairing-correlation parameter, Δ_n , for the odd- N nuclei, presumably the result of the "blocking" of the

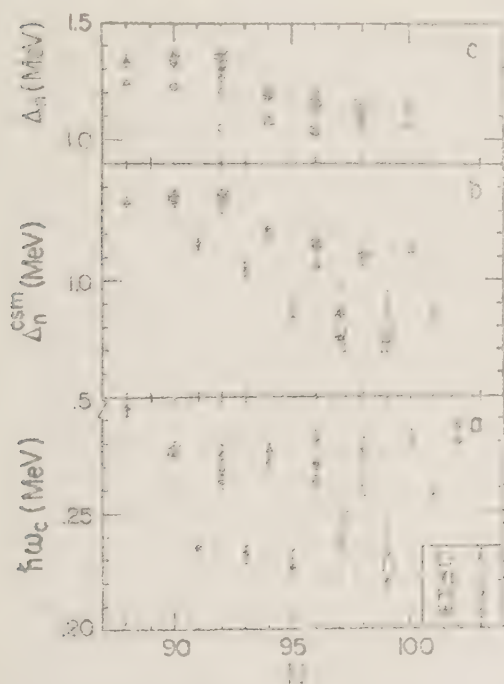


FIG. 2. (a) Systematics of $\hbar\omega_c$ for yrast bands in even-mass nuclei and for the lowest negative-parity band in odd- N nuclei. (b) Values of Δ_n^{CSM} necessary to reproduce the $\hbar\omega_c$'s in CSM calculations. The error bars only reflect uncertainties in the definition of the $\hbar\omega_c$'s and do not include model-dependent uncertainties resulting from the CSM calculations. (c) A comparison of Δ_n^{CSM} for even- N systems (solid symbols) with Δ_n^{oc} (open symbols) obtained from odd-even mass differences.

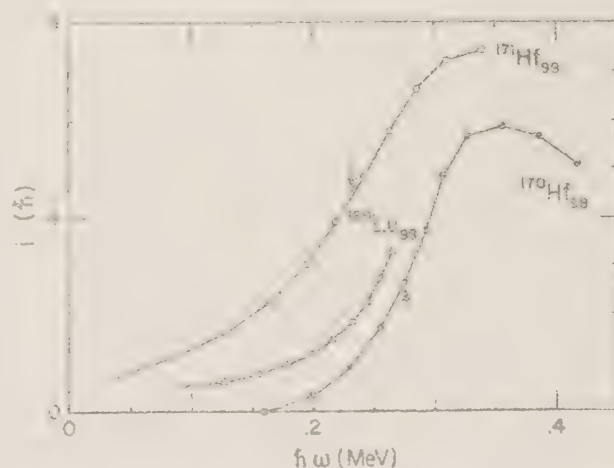


FIG. 3. Comparison of the alignments of the yrast bands in ^{169}Lu (favored and unfavored portions indicated by squares and triangles, respectively) and ^{170}Hf with that of the lowest negative-parity band of ^{171}Hf . The yrast band in ^{169}Lu aligns at frequencies comparable to that of the ^{170}Hf yrast band. For reference, the values of $\hbar\omega_c$ obtained from crossings in e' vs $\hbar\omega$ plots (see Fig. 1) are shown for $^{170,171}\text{Hf}$ by arrows.

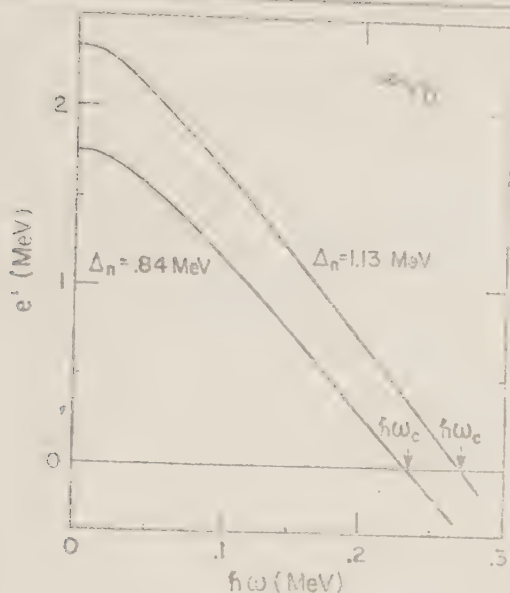


FIG. 4. Cranked shell-model two-quasiparticle Routhians as a function of $\hbar\omega$ for ^{166}Yb calculated with two different values Δ_n , indicating the shift in $\hbar\omega_c$ for a change in Δ_n .

pairing contribution from a quasineutron orbit near the Fermi surface. The values of Δ_n which reproduce the observed band crossings in CSM calculations, Δ_n^{CSM} , are shown in Fig. 2(b). In these calculations the deformations, ϵ_2 and ϵ_4 , were varied according to the prescription of Bengtsson¹¹ and the Fermi surface was chosen to reproduce the correct neutron number. The change in the predicted alignments of the quasineutron orbits between $N=90$, where the $[660]_{1/2}^+$ Nilsson configuration dominates, and $N=96$, where the Fermi surface is between the $[642]_{3/2}^+$ and the $[633]_{7/2}^+$ configurations, produces a decrease of Δ_n^{CSM} with mass number, which is superimposed on the odd-even variation resulting from the odd-even variation of $\hbar\omega_c$. It is emphasized that Δ_n^{CSM} is a parameter in the CSM calculations and, therefore, is not only model dependent, but also depends on the values of the other parameters in the calculations. Even the magnitude of such Δ_n^{CSM} values, however, becomes plausible when compared to Δ_n^{oe} 's obtained from the odd-even mass differences, Δ_n^{oe} —see Fig. 2(c). For $N=98-102$, where the deformations are stable, the values of Δ_n^{CSM} for even-even nuclei agree with Δ_n^{oe} . For $N=90-94$, where deformations are rapidly changing and where the nuclear masses are not known but are taken from systematics, there is no detailed agreement; however, the general decrease in the magnitude of Δ_n

with increasing N is reproduced. The increased magnitude of Δ_n near $N=90$, which is the result of a local increase in the number of states near the Fermi surface, is reproduced in BCS calculations.¹²

Evidence for a reduction of Δ_n in odd- N nuclei as compared to seniority-zero bands in even-even nuclei also has been obtained from the analysis of moments of inertia, α -decay intensities, and two-neutron transfer cross sections.¹³ It is difficult, however, to obtain quantitative results from the analysis of the moments of inertia and two-neutron transfer due to additional contributing effects. An $\approx 35\%$ reduction in Δ_n is indicated from α -decay intensities for actinide nuclei, but such studies are not possible for rare-earth nuclei. The reduction of Δ_n due to the "blocking" of the appropriate orbit near the Fermi surface is calculated¹² to be ≈ 200 keV.

The present results indicate that it also would be necessary to use a reduced Δ_n in CSM calculations for multi-quasineutron configurations in even- N nuclei. The value of Δ_n apparently does not depend upon the proton number. Therefore, no problem is involved in the use of a full-strength pairing-gap parameter in CSM calculations to reproduce the second "backbend" in the yrast band, if the explanation of this feature is the alignment of a pair of quaciprons.

In summary, an empirical odd-even neutron-number dependence of the angular frequency for the alignment of the first pair of $i_{1/2}$ quasineutrons is established. This behavior is explained by a reduction of Δ_n for odd- N systems as compared to the seniority-zero neutron configurations in even- N nuclei. A comparison of the magnitudes of the CSM Δ_n necessary to reproduce the crossing frequencies with values of Δ_n from odd-even mass differences indicates that it may be possible to obtain quantitative values of Δ from the crossing frequencies of quasiparticle bands. The agreement between Δ_n^{CSM} and Δ_n^{oe} also indicates that Δ_n is not strongly dependent upon $\hbar\omega$ for values of $\hbar\omega < \hbar\omega_c$. The loss in neutron pairing apparently is associated with neutron alignment and independent of proton alignment. It should be possible to reproduce the observed odd-even neutron-number systematics of the band-crossing frequencies in self-consistent calculations.

Discussions with S. Frauendorf, I. Hamamoto, Y. S. Chen, A. Bohr, and B. R. Mottelson are acknowledged. This work has been supported by the Danish Natural Science Research Council and

the Nordic Committee for Accelerator Based Research.

^(a)Permanent address: Institute of Nuclear Research, 05-400 Swierk, Poland.

^(b)Permanent address: Department of Physics, University of Manchester, Manchester M13 9PL, United Kingdom.

^(c)Permanent address: Department of Physics, University of Tennessee, Knoxville, Tenn. 37916.

^(d)Permanent address: Jagellonian University, 30-059 Cracow, Poland.

¹Aa. Bohr and B. Mottelson, *J. Phys. Soc. Jpn. Suppl.* **44**, 157 (1978), Proceedings of the International Conference on Nuclear Structure, Tokyo, 1977.

²R. Bengtsson and S. Frauendorf, *Nucl. Phys.* **A314**, 27 (1979), and **A327**, 139 (1979).

³L. L. Riedinger *et al.*, *Phys. Rev. Lett.* **44**, 568 (1980).

⁴F. S. Stephens and R. S. Simon, *Nucl. Phys.* **A183**, 257 (1972).

⁵I. Y. Lee *et al.*, *Phys. Rev. Lett.* **38**, 1454 (1977);

H. Ryde *et al.*, *Nucl. Phys.* **A207**, 513 (1973); O. C. Kistner *et al.*, *Phys. Rev. C* **17**, 1417 (1978); A. W. Sunyar *et al.*, *Phys. Lett.* **62B**, 283 (1976); A. Johnson *et al.*, *Nucl. Phys.* **A174**, 753 (1972); S. W. Yates *et al.*, *Phys. Rev. C* **21**, 2366 (1980); N. R. Johnson *et al.*, *Phys. Rev. Lett.* **40**, 151 (1978).

⁶W. Walus *et al.*, *Phys. Scr.* (to be published), and to be published; L. L. Riedinger, *Nucl. Phys.* **A347**, 141 (1980).

⁷L. L. Riedinger, *Phys. Scr.* **24**, 312 (1981); I. Rezanka *et al.*, *Phys. Rev. C* **11**, 1767 (1975); J. C. Lisle *et al.*, to be published; G. D. Dracoulis and P. M. Walker, *Nucl. Phys.* **A330**, 186 (1979); J. M. Aarts, thesis, University of Utrecht, 1981 (unpublished).

⁸G. D. Dracoulis *et al.*, *J. Phys. G* **4**, 713 (1978); P. M. Walker *et al.*, *J. Phys. G* **4**, 1655 (1978).

⁹C. Foin *et al.*, *Nucl. Phys.* **A199**, 129 (1973).

¹⁰C. Foin *et al.*, *Phys. Rev. Lett.* **35**, 1697 (1975).

¹¹R. Bengtsson, *J. Phys. (Paris), Colloq.* **41**, C10-84 (1980).

¹²S. G. Nilsson and O. Prior, *Mat. Fys. Medd. Dan. Vid. Selsk.* **32**, No. 16 (1961).

¹³Aa. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, 1975), Vol. II, Chaps. 4 and 5.

